

Quick Start Guide

NOEL-XCKU-EX

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1. Introduction

1.1. Overview

This document is a quick start guide for the NOEL-XCKU-EX design. The guide is mainly how-to oriented and does not go into many technical details. For more in-depth information we refer to respective products User's Manual. See the reference list below.

1.2. Availability

The FPGA bitstreams and software environment is available on the NOEL-XCKU-EX web page: <https://www.gaisler.com/NOEL-XCKU>.

1.3. Prerequisites

To use the provided bitstream, the user needs:

- Xilinx KCU105
- GRMON 3.2.9 evaluation version available at <https://www.gaisler.com/grmon>.
- Xilinx Vivado Design Suite to program the FPGA ([RD-7]).

1.4. References

Table 1.1. References

RD-1	NOEL-XCKU-EX User's Manual [https://www.gaisler.com/NOEL-XCKU]
RD-2	GRMON User's Manual [https://www.gaisler.com/doc/grmon3.pdf]
RD-3	RTEMS homepage [https://www.rtems.org]
RD-4	RTEMS User Manual [https://docs.rtems.org/branches/master/user/index.html]
RD-5	KCU105 Board User Guide [https://www.xilinx.com/support/documentation/boards_and_kits/kcu105/ug917-kcu105-eval-bd.pdf]
RD-6	Buildroot homepage [https://www.buildroot.com]
RD-7	Xilinx Vivado Design Suite [https://www.microsemi.com/product-directory/programming/4977-flashpro]

2. Overview

2.1. Boards

The NOEL-XCKU-EX design can be used with the Xilinx KCU105 ([RD-5]).

2.2. Design summary

The NOEL-XCKU-EX is a GRLIB design which includes the following features:

- Frontgrade Gaisler NOEL RISC-V RV64G processor
- RISC-V Debug module
- L2 cache with 256 KiB in 4 ways
- Memory controller and 1 GiB SDRAM.
- Ethernet 10/100/1000 Mbit MAC interface
- APBUART serial interface
- GRLIB AMBA AHB bus controller
- JTAG, Ethernet EDCL and UART debug link
- AHB bus trace
- 20-pin GPIO controller

For more details on the NOEL-XCKU-EX design, see the NOEL-XCKU-EX User's Manual ([RD-1]). For details about the the interfaces' connections in the board, see Chapter 3.

2.3. Processor features

- 64-bit architecture
- Hardware multiply and divide units
- Atomic instruction extension
- 32/64 bit floating point extensions using non-pipelined area efficient FPU or high-performance fully pipelined IEEE-754 FPU
- Machine, supervisor and user mode. RISC-V standard MMU with configurable TLB.
- User level interrupts
- RISC-V standard PLIC (platform interrupt controller)
- RISC-V standard PMP (physical memory protection)
- RISC-V standard external debug support
- Advanced 7-stage dual-issue in-order pipeline
- Dynamic branch prediction, branch target buffer and return address stack
- Four full ALUs, two of them late in the pipeline to reduce stalls
- Separate instruction and data L1 cache (Harvard architecture) with snooping

2.4. Software Development Environment

2.4.1. RTEMS

RTEMS is a hard Real Time Operating System.

The NOEL-V software development environment includes an RTEMS kernel, BSP tool chain and examples. This allows for development of real-time multitasking applications with POSIX support. The RTEMS tool chain is currently provided for the Linux 64-bit host operating systems.

Chapter 5 describes how to use RTEMS with NOEL-XCKU-EX.

The recommended method to load software onto NOEL-XCKU-EX is by connecting to a debug interface of the board through the GRMON hardware debugger (Chapter 4).

2.4.2. Bare C cross-compiler

NCC is a cross-compilation system for NOEL-V processors. It is based on the GNU compiler tools, the newlib C library and a support library for programming NOEL-V systems. The cross-compiler allows compilation of C and C++ single-threaded applications.

Chapter 6 describes how to use NCC with NOEL-XCKU-EX.

2.4.3. Linux

Buildroot can be used to easily create a bootable Linux image for NOEL-V [RD-6]. It automatically creates a toolchain and supports a large number of useful userspace applications which can be included in the generated root file system. Included in the software development environment is a NOEL-XCKU-EX BSP for Buildroot which provides the necessary driver support.

See Chapter 7 for instructions on how to create a Linux image for NOEL-XCKU-EX with Buildroot.

2.4.4. VxWorks 7

Please contact support@gaisler.com for information about NOEL-V BSPs for VxWorks 7.

2.4.5. GRMON

GRMON is a hardware monitor which allows non-intrusive debugging and execution control of software on NOEL-XCKU-EX. GRMON provides a RISC-V GDB server. GRMON is available for Linux and Windows host operating systems.

NOEL-V can be used with GRMON GUI.

Chapter 4 describes how to use GRMON with NOEL-XCKU-EX.

3. Board Configuration

This chapter describes boards items as used by the NOEL-XCKU-EX design.

Please see KCU105 Board User Guide for a detailed legend of the reference designators.

3.1. Buttons and switches

- SW12[1..4] DIP switch: GPIO0 inputs 0, 1, 2, 3.
- SW7, SW8, SW9, SW10 buttons: GPIO0 inputs 4, 5, 6, 7
- CPU_RST button: Main reset to the FPGA design

The Switch SW12[1] also acts as select signal for the UART interface.

- When '1' the UART interface is connected to the UART debug link (AHBUART).
- When '0' the UART interface is connected to the APBUART.

3.2. LEDs

- LED[0..3]: Connected to GPIO0 outputs 16, 17, 18, 19
- LED[4]: Connected to SW12[1]
- LED[6..7]: When ON they indicate that the memory controller calibration is complete and the FPGA design has access to the on-board SDRAM.

3.3. Connectors

- J87: USB JTAG interface via Digilent module with micro-B USB connector. See (Chapter 4).
- J4: USB UART interface. AHBUART debug link or APBUART function selectable by SW12[1].
- Ethernet PHY SGMII interface with RJ-45 connector. See (Chapter 4).
- J52: PMOD Connector GPIO0 I/O 8-15.

3.4. Memories

The NOEL-XCKU-EX has 1 GiB of SDRAM available on the on-chip bus.

3.5. Programming the bitstream

A Xilinx Vivado script to program the FPGA is provided with the bitfile distribution. The bitstream folder contains several bitstreams which represent different configurations of the processor (EX1, EX2, ecc.). Select one of the bitstreams (described in [RD-1]), and follow the instructions below to program the FPGA:

To program the FPGA please follow these instructions:

1. Connect the PC and the board using a standard micro-USB cable into the connector USB-JTAG J87.
2. Make sure that Vivado is added to your path variables
3. Open a terminal in the downloaded folder and issue the following command to launch Vivado:

```
vivado -mode tcl -notrace -source doprog.tcl
```

4. To program the FPGA with the selected configuration, run in the Vivado console (in this case for EX1):

```
doprogram EX1
```

5. Once the FPGA has been programmed, it is possible to connect to the board using GRMON, using the command:

```
grmon -digilent
```

Please see (Chapter 4) for further information regarding GRMON and the available debug links.

Alternatively, the bitfile (.bit) can be programmed to the Xilinx KCU105 using the Vivado design suite graphical interface. Start Vivado and select the menu item *Flow -> Open Hardware Manager*. Once the FPGA has been programmed, remember to close the hardware manager before connecting with GRMON.

3.6. FPGA configuration mode

The board switch SW15 [6] selects the configuration mode for the FPGA device. It is a board configuration and not part of the NOEL-V design.

- 0: Master SPI configuration mode
- 1: JTAG configuration mode

The default and recommended configuration is to set SW15 [6] in position 0 to use SPI configuration mode.

4. GRMON hardware debugger

4.1. Overview

GRMON is a debug monitor used to develop and debug GRLIB systems with NOEL and LEON processors. The target system, including the processor and peripherals, is accessed on the AHB bus through a debug-link connected to the host computer. GRMON has GDB support which makes C/C++ level debugging possible by connecting GDB to the GRMON's GDB socket.

With GRMON one can for example:

- Inspect NOEL-V and peripheral registers
- Upload applications to RAM with the **load** command.
- Program the FLASH with the **flash** command.
- Control execution flow by starting applications (**run**), continue execution (**cont**), single-stepping (**step**), inserting breakpoints/watchpoints (**bp**) etc.
- Inspect the current CPU state listing the back-trace, instruction trace and disassemble machine code.

The first step is to set up a debug link in order to connect to the board. The following section outlines which debug interfaces are available and how to use them on the NOEL-XCKU-EX design. After that, a basic first inspection of the board is exemplified.

GRMON is described on the homepage [<https://www.gaisler.com/index.php/products/debug-tools>] and in detail in the GRMON User Manual [RD-2].

4.2. NOEL-V support

Most of the GRMON commands available for LEON are also available for NOEL-V. GRMON commands available for NOEL-V include:

- **load**: RISC-V ELF file support. Symbols are loaded from the ELF file and can be used instead of addresses for most commands.
- **run, cont, go, step**: execution control
- **mem, wmem**: read/write any on-chip address.
- **disassemble**: RISC-V instruction disassembly
- **inst**: CPU instruction trace
- **bp**: Hardware and software breakpoint
- **bt**: call tree backtrace, based on dwarf debug information
- **reg**: read and write all RISC-V CPU general purpose registers and CSR registers. CSR registers can be specified by name or address.
- **mmu**: inspect and walk MMU tables
- **forward**: UART forwarding to the GRMON console
- **info reg, info sys**: Supports the NOEL-V related GRLIB devices.
- **gdb**: Creates a GDB server for connecting with a GDB compiled with RISC-V as target.

4.3. NOEL-V limitations

- GRMON can report only the following reasons for termination of execution:
 - An ebreak instruction was executed.
 - The signal `haltreq` was asserted by the debug module. Typically as a consequence of the user hitting `ctrl+c` in the GRMON terminal.

In the current NOEL-V release, execution can not be aborted at an arbitrary exception or hardware breakpoint.

- CPU local AHB trace is not available. The NOEL-XCKU-EX design includes an AHBTRACE which can be controlled with the GRMON command **at**.

The limitations listed above are present in the current release of NOEL-V. The features mentioned are part of the schedule for future releases.

4.4. Debug-link alternatives

4.4.1. Connecting via the Digilent USB/JTAG interface

Please see GRMON User's Manual for information on how to set up the required Digilent Adept driver software. Then connect the PC and the board using a standard USB cable into the USB-micro J87 USB-JTAG connector and issue the following command:

```
grmon -digilent
```

4.4.2. Connecting via the Ethernet debug interfaces

If another address is wanted for the Ethernet debug link then one of the other debug links must be used to connect GRMON to the board. The EDCL IP address can then be changed using GRMON's **edcl** command. This new address will persist until next system reset.

With the Ethernet Debug Communication Link 0 address set to 192.168.0.51 the GRMON command to connect to the board is:

```
grmon -eth 192.168.0.51
```

4.4.3. Connecting via the serial UART

Make sure the switch SW12[1] is selecting the UART debug link. Please see GRMON User's Manual for instructions how to connect GRMON to a board using a serial UART connection. The PC is connected using a standard USB cable to serial converter) to the USB-micro J4 USB-UART connector and then starting GRMON without debug-link option (default is UART) or by specifying which PC UART using the `-uart COMPORT_NAME` command line switch. For example:

```
grmon -uart /dev/ttyUSB0
```

4.5. First steps

The previous sections have described which debug-links are available and how to start using them with GRMON. The subsections below assume that GRMON, the host computer and the NOEL-XCKU-EX board have been set up so that GRMON can connect to the board.

When connecting to the board for the first time it is recommended to get to know the system by inspecting the current configuration and hardware present using GRMON. With the **info sys** command more details about the system is printed and with **info reg** the register contents of the I/O registers can be inspected. Below is a list of items of particular interest:

- AMBA system frequency is printed out at connect, if the frequency is wrong then it might be due to noise in auto detection (small error). See `-freq` flag in the GRMON User's Manual [RD-2].
- Memory location and size configuration is found from the **info sys** output.
- If the Ethernet debug link is present, one can view and change the EDCL IP using the **edcl** command as described in the GRMON User's Manual [RD-2].

4.6. Connecting to the board

In the following example a JTAG debug link is used to connect to the board. The auto-detected frequency, memory parameters and stack pointer are verified by looking at the GRMON terminal output below.

```
grmon -digilent
GRMON debug monitor v3.2.3 64-bit version

Copyright (C) 2020 Frontgrade Gaisler - All rights reserved.
For latest updates, go to http://www.gaisler.com/
Comments or bug-reports to support@gaisler.com
```

Commands missing help:

```
Device ID:          0x287
GRLIB build version: 4251
Detected frequency: 80.0 MHz
```

Component	Vendor
AHB Debug UART	Frontgrade Gaisler
JTAG Debug Link	Frontgrade Gaisler
GR Ethernet MAC	Frontgrade Gaisler
NOEL-V RISC-V Processor	Frontgrade Gaisler
NOEL-V RISC-V Processor	Frontgrade Gaisler

```

AHB-to-AHB Bridge           Frontgrade Gaisler
RISC-V Debug Module        Frontgrade Gaisler
AHB/APB Bridge             Frontgrade Gaisler
AMBA Trace Buffer          Frontgrade Gaisler
L2-Cache Controllor       Frontgrade Gaisler
Generic AHB ROM            Frontgrade Gaisler
Xilinx MIG Controller      Frontgrade Gaisler
AHB/APB Bridge            Frontgrade Gaisler
RISC-V CLINT               Frontgrade Gaisler
RISC-V PLIC                Frontgrade Gaisler
AHB Status Register        Frontgrade Gaisler
General Purpose I/O port   Frontgrade Gaisler
Generic UART                Frontgrade Gaisler
Version and Revision Register Frontgrade Gaisler
Modular Timer Unit         Frontgrade Gaisler

```

Use command 'info sys' to print a detailed report of attached cores

```
grmon3> info sys
```

```

ahbuart0 Frontgrade Gaisler  AHB Debug UART
        AHB Master 0
        APB: 80000e00 - 80000f00
        Baudrate 115200, AHB frequency 80.00 MHz
ahbjtag0 Frontgrade Gaisler  JTAG Debug Link
        AHB Master 1
greth0   Frontgrade Gaisler  GR Ethernet MAC
        AHB Master 2
        APB: 80000500 - 80000600
        IRQ: 5
        1000 Mbit capable
        edcl ip 192.168.0.222, buffer 2 kbyte
cpu0     Frontgrade Gaisler  NOEL-V RISC-V Processor
        AHB Master 0
cpul     Frontgrade Gaisler  NOEL-V RISC-V Processor
        AHB Master 1
ahb2ahb0 Frontgrade Gaisler  AHB-to-AHB Bridge
        AHB Master 3
        AHB: 00000000 - 80000000
        AHB: 80000000 - 90000000
        AHB: e0000000 - 00000000
        USR: 00000111
        USR: ffe00000
dm0      Frontgrade Gaisler  RISC-V Debug Module
        AHB: 90000000 - a0000000
        hart0: DXLEN 64, MXLEN 64, SXLEN 64, UXLEN 64
                ISA A I M, Modes M S U
                Stack pointer 0x7fffffff0
                icache 4 * 4 kB, 32 B/line, rnd
                dcache 4 * 4 kB, 32 B/line, rnd
                2 triggers
        hart1: DXLEN 64, MXLEN 64, SXLEN 64, UXLEN 64
                ISA A I M, Modes M S U
                Stack pointer 0x7fffffff0
                icache 4 * 4 kB, 32 B/line, rnd
                dcache 4 * 4 kB, 32 B/line, rnd
                2 triggers
apbmst0  Frontgrade Gaisler  AHB/APB Bridge
        AHB: 80000000 - 80100000
ahbtrace0 Frontgrade Gaisler  AMBA Trace Buffer
        AHB: fff00000 - fff20000
        Trace buffer size: 128 lines
l2cache0 Frontgrade Gaisler  L2-Cache Controllor
        AHB: 40000000 - 80000000
        AHB: ff000000 - ff400000
        USR: 00000110
        L2C: 4-ways, cachesize: 256 kbytes, mtrr: 0, AHB SPLIT support
ahbrom0  Frontgrade Gaisler  Generic AHB ROM
        AHB: 00000000 - 00100000
        32-bit ROM: 1 MB @ 0x00000000
mig0     Frontgrade Gaisler  Xilinx MIG Controller
        AHB: 40000000 - 80000000
        SDRAM: 1024 Mbyte
apbmst1  Frontgrade Gaisler  AHB/APB Bridge
        AHB: 80000000 - 80100000
clint0   Frontgrade Gaisler  RISC-V CLINT
        AHB: e0100000 - e0200000
plic0    Frontgrade Gaisler  RISC-V PLIC
        AHB: 84000000 - 88000000
        4 contexts, 32 interrupt sources
ahbstat0 Frontgrade Gaisler  AHB Status Register
        APB: 80000f00 - 80001000
        IRQ: 4
gpio0    Frontgrade Gaisler  General Purpose I/O port
        APB: 80000400 - 80000500

```

```

uart0      Frontgrade Gaisler  Generic UART
          APB: 80000100 - 80000200
          IRQ: 1
          Baudrate 38461, FIFO debug mode available
adev18     Frontgrade Gaisler  Version and Revision Register
          APB: 80000200 - 80000300
gptimer0   Frontgrade Gaisler  Modular Timer Unit
          APB: 80000300 - 80000400
          IRQ: 2
          16-bit scalar, 2 * 32-bit timers, divisor 80

grmon3> info reg
GR Ethernet MAC
  0x80000500 Control register          0x9d000000
  0x80000504 Status register          0x11000000
  0x80000508 MAC address MSB          0x00000000
  0x8000050c MAC address LSB          0x00000000
  0x80000510 MDIO register            0x7949384a
  0x80000514 Tx descriptor register    0x00000000
  0x80000518 Rx descriptor register    0x00000000
  0x8000051c EDCL IP register          0xc0a800de
  0x80000520 Hash table MSB register    0x00000000
  0x80000524 Hash table LSB register    0x00000000
  0x80000528 ECDL MAC address MSB      0x00000200
  0x8000052c ECDL MAC address LSB      0x00000009
NOEL-V RISC-V Processor
  ISA and extensions                   0x800000000141101
  Machine status register (mstatus)     0x0000000a00000000
  Machine interrupt pending (mip)       0x0000000000000000
NOEL-V RISC-V Processor
  ISA and extensions                   0x800000000141101
  Machine status register (mstatus)     0x0000000a00000000
  Machine interrupt pending (mip)       0x0000000000000000
RISC-V Debug Module
  0x90000010 Abstract Data 0           0x00000000
  0x90000014 Abstract Data 1           0x00000000
  0x90000018 Abstract Data 2           0x00000000
  0x9000001c Abstract Data 3           0x00000000
  0x90000040 Debug Module Control      0x00010001
  0x90000044 Debug Module Status       0x00030382
  0x90000048 Hart Info                 0x00200000
  0x90000050 Hart Array Window Select  0x00000000
  0x90000054 Hart Array Window        0x00000003
  0x90000058 Abstract Control and Status 0x08000004
  0x9000005c Abstract Command          0x00320344
  0x90000074 Next Debug Module         0x00000000
  0x9000007c Custom Features           0x00000000
  0x90000080 Program Buffer 0           0x0000100f
  0x90000084 Program Buffer 1           0x00100073
  0x90000088 Program Buffer 2           0x10c2a283
  0x9000008c Program Buffer 3           0x00100073
  0x90000090 Program Buffer 4           0x00100073
  0x90000094 Program Buffer 5           0x00100073
  0x90000098 Program Buffer 6           0x00100073
  0x9000009c Program Buffer 7           0x00100073
  0x900000c0 Authentication Data       0x00000000
  0x900000c8 Debug Module Control and Status 2 0x00000000
  0x90000100 Halt Summary 0            0x00000003
  0x900001c0 Custom Features 0          0x00000000
  0x900001c4 Custom Features 1          0x00000000
  0x900001c8 Custom Features 2          0x00000000
  0x900001cc Custom Features 3          0x00000000
  0x900001d0 Custom Features 4          0x00000000
  0x900001d4 Custom Features 5          0x00000000
  0x900001d8 Custom Features 6          0x00000000
  0x900001dc Custom Features 7          0x00000000
  0x900001e0 Custom Features 8          0x00000000
  0x900001e4 Custom Features 9          0x00000000
  0x900001e8 Custom Features 10         0x00000000
  0x900001ec Custom Features 11         0x00000000
  0x900001f0 Custom Features 12         0x00000000
  0x900001f4 Custom Features 13         0x00000000
  0x900001f8 Custom Features 14         0x00000000
  0x900001fc Custom Features 15         0x00000000
AMBA Trace Buffer
  0xfff00000 Trace buffer control register 0x00008080
  0xfff00004 Trace buffer index register  0x000007f0
  0xfff00008 Trace buffer time tag counter 0x00000000
  0xfff0000c Trace buffer mst/slv filter register 0x00000000
  0xfff00010 Trace buffer bp 1 address    0x00000000
  0xfff00014 Trace buffer bp 1 mask      0x00000000
  0xfff00018 Trace buffer bp 2 address    0x00000000
  0xfff0001c Trace buffer bp 2 mask      0x00000000
L2-Cache Controller
  0xff000000 L2C Control register        0x80040000

```

0xff000004	L2C Status register	0x46002103
0xff000020	L2C Error status/control	0x02000000
RISC-V CLINT		
0xe0100000	hart0 msip	0x00000000
0xe0104000	hart0 mtimecmp lo	0xffffffff
0xe0104004	hart0 mtimecmp hi	0xffffffff
0xe0100004	hart1 msip	0x00000000
0xe0104008	hart1 mtimecmp lo	0xffffffff
0xe010400c	hart1 mtimecmp hi	0xffffffff
0xe0100008	hart2 msip	0x00000000
0xe0104010	hart2 mtimecmp lo	0x00000000
0xe0104014	hart2 mtimecmp hi	0x00000000
0xe010000c	hart3 msip	0x00000000
0xe0104018	hart3 mtimecmp lo	0x00000000
0xe010401c	hart3 mtimecmp hi	0x00000000
0xe010bfff	mtime lo	0x00000000
0xe010bffc	mtime hi	0x00000000
RISC-V PLIC		
0x84000004	Interrupt source 1 priority	0x00000000
0x84000008	Interrupt source 2 priority	0x00000000
0x8400000c	Interrupt source 3 priority	0x00000000
0x84000010	Interrupt source 4 priority	0x00000000
0x84000014	Interrupt source 5 priority	0x00000000
0x84000018	Interrupt source 6 priority	0x00000000
0x8400001c	Interrupt source 7 priority	0x00000000
0x84000020	Interrupt source 8 priority	0x00000000
0x84000024	Interrupt source 9 priority	0x00000000
0x84000028	Interrupt source 10 priority	0x00000000
0x8400002c	Interrupt source 11 priority	0x00000000
0x84000030	Interrupt source 12 priority	0x00000000
0x84000034	Interrupt source 13 priority	0x00000000
0x84000038	Interrupt source 14 priority	0x00000000
0x8400003c	Interrupt source 15 priority	0x00000000
0x84000040	Interrupt source 16 priority	0x00000000
0x84000044	Interrupt source 17 priority	0x00000000
0x84000048	Interrupt source 18 priority	0x00000000
0x8400004c	Interrupt source 19 priority	0x00000000
0x84000050	Interrupt source 20 priority	0x00000000
0x84000054	Interrupt source 21 priority	0x00000000
0x84000058	Interrupt source 22 priority	0x00000000
0x8400005c	Interrupt source 23 priority	0x00000000
0x84000060	Interrupt source 24 priority	0x00000000
0x84000064	Interrupt source 25 priority	0x00000000
0x84000068	Interrupt source 26 priority	0x00000000
0x8400006c	Interrupt source 27 priority	0x00000000
0x84000070	Interrupt source 28 priority	0x00000000
0x84000074	Interrupt source 29 priority	0x00000000
0x84000078	Interrupt source 30 priority	0x00000000
0x8400007c	Interrupt source 31 priority	0x00000000
0x84000080	Interrupt source 32 priority	0x00000000
0x84001000	Interrupt Pending bit 0-31	0x00000010
0x84001004	Interrupt Pending bit 32-63	0x00000000
0x84002000	context 0 enable source 0-31	0x00000000
0x84002004	context 0 enable source 32-63	0x00000000
0x84002080	context 1 enable source 0-31	0x00000000
0x84002084	context 1 enable source 32-63	0x00000000
0x84002100	context 2 enable source 0-31	0x00000000
0x84002104	context 2 enable source 32-63	0x00000000
0x84002180	context 3 enable source 0-31	0x00000000
0x84002184	context 3 enable source 32-63	0x00000000
0x84200000	context 0 priority threshold	0x00000001
0x84201000	context 1 priority threshold	0x00000001
0x84202000	context 2 priority threshold	0x00000001
0x84203000	context 3 priority threshold	0x00000001
AHB Status Register		
0x80000f00	Status register	0x0000001a
0x80000f04	Failing address register	0x80000f00
General Purpose I/O port		
0x80000400	I/O port data register	0x0000ff0c
0x80000404	I/O port output register	0x00000000
0x80000408	I/O port direction register	0x00000000
0x8000040c	I/O interrupt mask register	0x00000000
0x80000410	I/O interrupt polarity register	0x00000000
0x80000414	I/O interrupt edge register	0x00000000
0x8000041c	Capability register	0x00000013
Generic UART		
0x80000104	UART Status register	0x00000086
0x80000108	UART Control register	0x80000003
0x8000010c	UART Scaler register	0x00000103
Modular Timer Unit		
0x80000300	Scalar value register	0x0000004f
0x80000304	Scalar reload value register	0x0000004f
0x80000308	Configuration register	0x00000112
0x80000310	Timer 0 Value register	0xffffffff
0x80000314	Timer 0 Reload value register	0xffffffff

```

0x80000318 Timer 0 Control register          0x00000043
0x80000320 Timer 1 Value register           0x00000000
0x80000324 Timer 1 Reload value register    0x00000000
0x80000328 Timer 1 Control register         0x00000040

```

4.7. Get system information

One can limit the output to certain cores by specifying the core(s) name(s) to the **info sys** and **info reg** commands. As seen below the memory parameters, first UART and first Timer core information is listed.

```

grmon3> info sys mig0
mig0      Frontgrade Gaisler  Xilinx MIG DDR3 Controller
          AHB: 40000000 - 80000000
          SDRAM: 1024 Mbyte

grmon3> info sys uart0 gptimer0
uart0     Frontgrade Gaisler  Generic UART
          APB: 80000100 - 80000200
          IRQ: 1
          Baudrate 38422, FIFO debug mode available
gptimer0  Frontgrade Gaisler  Modular Timer Unit
          APB: 80000300 - 80000400
          IRQ: 2
          16-bit scalar, 2 * 32-bit timers, divisor 80

grmon3> info reg -v ahbstat0
AHB Status Register
0x80000f00 Status register          0x00000012
  9   ce          0x0          Correctable error
  8   ne          0x0          New error
  7   hw          0x0          HWRITE on error
  6:3 hm          0x2          HMASTER on error
  2:0 hs          0x2          HSIZE on error

0x80000f04 Failing address register    0x80000f00

```

4.8. Load a RAM application

An application linked to RAM can be loaded directly with the **load** command and run with the **run** command. The **dtb** command is used to load a device tree description for the board. In the example below, the file `board.dtb` should be changed into the name of the target board `.dtb` file.

```

grmon3> load hello.elf
40000000 .text          142.0kB / 142.0kB  [=====] 100%
400237D0 .rtmsroset      96B          [=====] 100%
40024840 .data          4.4kB / 4.4kB  [=====] 100%
Total size: 146.44kB (777.96kbit/s)
Entry point 0x40000000
Image hello.elf loaded

grmon3> forward enable uart0
I/O forwarding to uart0 enabled

grmon3> dtb board.dtb
DTB will be loaded to the stack

grmon3> run

hello, world

CPU 0: Forced into debug mode
0x4001607c: 00100073 ebreak <_CPU_Fatal_halt+36>
CPU 1: Interrupted!
0x40011018: 10500073 wfi <_CPU_Thread_Idle_body+0>

```

The line `hello, world` is the program output which is forwarded to the GRMON terminal.

4.9. Debugging with GDB

It possible to connect the GDB debugger to GRMON to be able to debug programs at source level. Either start GRMON with the `-gdb` flag or enter the `gdb` command in GRMON.

```

grmon3> gdb
Started GDB service on port 2222.

```

GDB is included with the RTEMS toolchain as `riscv-rtems5-gdb`:

```
user@workstation:~$ riscv-rtems5-gdb
GNU gdb (GDB) 8.3
Copyright (C) 2019 Free Software Foundation, Inc.
License GPLv3+: GNU GPL version 3 or later <http://gnu.org/licenses/gpl.html>
This is free software: you are free to change and redistribute it.
There is NO WARRANTY, to the extent permitted by law.
Type "show copying" and "show warranty" for details.
This GDB was configured as "--host=x86_64-pc-linux-gnu --target=riscv-rtems5".
Type "show configuration" for configuration details.
For bug reporting instructions, please see:
<http://www.gnu.org/software/gdb/bugs/>.
Find the GDB manual and other documentation resources online at:
<http://www.gnu.org/software/gdb/documentation/>.

For help, type "help".
Type "apropos word" to search for commands related to "word".
(gdb)
```

Specify the filename of the image to debug using the file command:

```
(gdb) file /home/user/riscv/demo/hello/hello.exe
Reading symbols from /home/user/riscv/demo/hello/hello.exe...
```

Connect to GRMON using target extended-remote:

```
(gdb) target extended-remote :2222
Remote debugging using :2222
0x0000000000000000 in ?? ()
```

The image can be loaded onto the target using the load command. This needs to be done before starting or restarting the program.

```
(gdb) load
Loading section .start, size 0x4c lma 0x40000000
Loading section .text, size 0x132e8 lma 0x4000004c
Loading section .rodata, size 0x120a0 lma 0x40013338
Loading section .sdata2, size 0x30 lma 0x400253d8
Loading section .eh_frame, size 0x4 lma 0x40025408
Loading section .init_array, size 0x8 lma 0x40025410
Loading section .fini_array, size 0x8 lma 0x40025418
Loading section .rtmsroset, size 0x68 lma 0x40025420
Loading section .data, size 0x768 lma 0x40025488
Loading section .htif, size 0x1000 lma 0x40025c00
Loading section .sdata, size 0xa8 lma 0x40027000
Start address 0x40000000, load size 158864
Transfer rate: 62 KB/sec, 7943 bytes/write.
```

RTEMS images expect register a1 to contain a pointer to a device tree description. This can be set up with the dtb command provided by GRMON. Use the mon prefix to execute a command in GRMON and load the device tree using dtb:

```
(gdb) mon dtb noel-xilinx-kcul05.dtb
DTB will be loaded to the stack
```

Use the break command to insert a breakpoint at the Init function:

```
(gdb) break Init
Breakpoint 1 at 0x40000170: file test.c, line 13.
```

The program can now be executed using the run command. GDB should break the execution once the program reaches the Init function.

```
(gdb) run
The program being debugged has been started already.
Start it from the beginning? (y or n) y
Starting program: /home/user/riscv/demo/hello/hello.exe

Breakpoint 1, Init (ignored=1073914168) at test.c:13
```

```
13 puts("");
```

At this stage one can, for example, step through the program with `step` or `next`, print the values of variables with `p`, or continue execution with the `cont` command.

```
(gdb) cont
Continuing.

hello, world
```

The following message is printed if the RTEMS program exits normally.

```
*** FATAL ***
fatal source: 5 (RTEMS_FATAL_SOURCE_EXIT)
fatal code: 0 (0x00000000)
RTEMS version: 5.0.0.94bddc9c5daf258a8d0981e63bf4180b7b249677
RTEMS tools: 9.3.0 20200312 (RTEMS 5, RSB 5 (3bd11fd4898b), Newlib 7947581)
executing thread ID: 0x08a010001
executing thread name: UI1

Program received signal SIGTRAP, Trace/breakpoint trap.
_CPU_Fatal_halt (source=source@entry=5, error=error@entry=0)
at /home/user/riscv/leon-rtms/build/./c/src/lib/libbsp/riscv/riscv/
./../../../../../../../../bsp/riscv/riscv/start/bsp_fatal_halt.c:43
43     asm ("ebreak");
(gdb)
```


5. RTEMS Real Time Operating System

5.1. Overview

RTEMS is a real time operating system that supports many processor families [RD-3]. Frontgrade Gaisler distributes a precompiled RTEMS toolchain for NOEL-V. This section gives the reader a brief introduction on how to use RTEMS together with the NOEL-XCKU-EX design. It will be demonstrated how to install the toolchain and build an existing sample RTEMS project and run it on the board using GRMON.

The NOEL-V RTEMS distribution includes a prebuilt toolchain with GNU Binutils, GCC and Newlib. The supported host operating system is Linux. It also contains prebuilt RTEMS kernels for the NOEL-V, including 32-bit and 64-bit versions. Support is included for the NOEL-XCKU-EX interrupt controller, timer and UART.

Sample RTEMS projects are available within the toolchain package, installed in the `examples` directory.

5.2. Features

- Kernel:
 - BSP variants for `rv32i`, `rv32im`, `rv32ima`, `rv32imafd`, `rv64im`, `rv64ima` and `rv64imafd`.
 - Uni-processor and SMP kernels available.
 - RTEMS POSIX support
 - Based on RTEMS master as of June 2020. (Exact `rtems.git` commit hash can be found in the `README` file in the root directory of the toolchain distribution.)
- NOEL-V BSP
 - Console driver for APBUART
 - Interrupt controller (PLIC and CLINT)
 - Clock driver via CLINT `mtime`
- GCC 9.3.0

5.3. Install toolchain and kernel

The toolchain and source can be downloaded from <https://www.gaisler.com/NOEL-XCKU>.

First extract the toolchain and kernel archive into `/opt`. In order for the compiler to be found, the binary directory `/opt/rtems-noel-1.0.4/bin` has to be added to the `PATH` variable as below:

```
$ cd /opt
$ tar xf rtems-noel-1.0.4.tar.bz2
$ export PATH=$PATH:/opt/rtems-noel-1.0.4/bin
```

5.4. Building an RTEMS sample application

Once the toolchain is set up, you can compile and link a sample RTEMS application by doing:

```
$ cd /opt/rtems-noel-1.0.4/examples/hello
$ make
riscv-rtems5-gcc --pipe -march=rv64ima -mabi=lp64 \
  -B/opt/rtems-noel-1.0.4/kernel/riscv-rtems5/now64ima/lib \
  -specs bsp_specs -qrtems -c test.c -o test.o
riscv-rtems5-gcc --pipe -march=rv64ima -mabi=lp64 \
  -B/opt/rtems-noel-1.0.4/kernel/riscv-rtems5/now64ima/lib \
  -specs bsp_specs -qrtems -Wl,--gc-sections test.o -o hello.exe
```

The default load address is at the start of the RAM, i.e. `0x00000000`.

See Chapter 8 for more information on the available examples.

5.5. Running and debugging with GRMON

Once your executable is compiled, connect to your NOEL-XCKU-EX with GRMON. The following log shows how to load and run an executable. Note that the console output is redirected to GRMON by the use of the `-u` command line switch, so that target application console output (APBUART) is shown directly in the GRMON console.

Example 5.1.

```
$ grmon -digilent -u
GRMON debug monitor v3.2.9 64-bit version

grmon3> dtb board.dtb
DTB will be loaded to the stack

grmon3> load hello.exe
00000000 .start          76B          [=====>] 100%
0000004C .text           98.6kB / 98.6kB [=====>] 100%
00018AB0 .rodata        83.5kB / 83.5kB [=====>] 100%
0002D8E0 .sdata2         48B          [=====>] 100%
0002D910 .eh_frame        4B           [=====>] 100%
0002D918 .init_array      8B           [=====>] 100%
0002D920 .fini_array       8B           [=====>] 100%
0002D928 .rtemsroset     112B         [=====>] 100%
0002D998 .data            2.3kB / 2.3kB [=====>] 100%
0002E2C0 .htif            4.0kB / 4.0kB [=====>] 100%
00030000 .sdata            208B         [=====>] 100%
Total size: 188.86kB (1.12Mbit/s)
Entry point 0x00000000
Image hello.exe loaded

grmon3> run

hello, world

CPU 0: Forced into debug mode
0x0001607c: 00100073 ebreak <_CPU_Fatal_halt+36>
CPU 1: Interrupted!
0x00011018: 10500073 wfi <_CPU_Thread_Idle_body+0>

grmon3>
```

To debug the compiled program you can insert break points, step and continue directly from the GRMON console. Compilation symbols are loaded automatically by GRMON once you load the executable. An example is provided below.

```
grmon3> load hello.exe
[...]
Total size: 188.86kB (1.12Mbit/s)
Entry point 0x00000000
Image hello.exe loaded

grmon3> bp Init
Software breakpoint 1 at <Init>

grmon3> run

Breakpoint 1 hit
0x00000118: 1141 addi sp, sp, -16 <Init+0>

grmon3> inst 5
TIME L P ADDRESS INSTRUCTION RESULT SYMBOL
593654 1 M 0000705a jalr ra, a5 [000000000000705C] _Thread_Handler+0x4e
593658 1 M 00007684 ld t1, 272(a0) [0000000000000118] _Thread_Entry_adaptor_numeric+0x0
593660 0 M 00007688 ld a0, 280(a0) [00000000000023128] _Thread_Entry_adaptor_numeric+0x4
593660 1 M 0000768c jalr zero, t1 [000000000000768E] _Thread_Entry_adaptor_numeric+0x8
593695 0 M 00000118 addi sp, sp, -16 [ BREAKPOINT ] Init+0x0

grmon3> step
0x4000013c: 4002e537 lui a0, 0x4002e <Init+0>

grmon3> inst 5
TIME L P ADDRESS INSTRUCTION RESULT SYMBOL
593660 0 M 00007688 ld a0, 280(a0) [00000000000023128] _Thread_Entry_adaptor_numeric+0x4
593660 1 M 0000768c jalr zero, t1 [000000000000768E] _Thread_Entry_adaptor_numeric+0x8
593695 0 M 00000118 ebreak [ BREAKPOINT ] Init+0x0
593728 0 M 00000118 addi sp, sp, -16 [0000000000029D70] Init+0x0
593729 0 M 0000011a sd s0, 0(sp) [0000000000029D70] Init+0x2

grmon3> reg
a0: 0000000040023128 t0: 7F7F7F7FFFFFFFFF s0: 0000000040021A48
a1: 0000000000000000 t1: 0000000040000118 s1: 0000000000000000
a2: 000000004001ECC8 t2: FFFFFFFFFFFFFFFF s2: 0000000000000000
a3: 00000000A010001 t3: 0000000000000000 s3: 0000000000000000
a4: 0000000000000000 t4: 0000000000000002 s4: 0000000000000000
```

```

a5: 0000000040007684    t5: 00000000000021ED    s5: 0000000000000000
a6: 0000000021DAE500    t6: FFFFFFFF00000000    s6: 0000000000000000
a7: 0000000021DAE500    tp: 0000000000000000    s7: 0000000000000000
sp: 00000000000029D70    gp: 0000000000020800    s8: 0000000000000000
mstatus: 0000000A00000008 mip: 000    mie: 800    s9: 0000000000000000
ra: 000000000000705C    s10: 0000000000000000
pc: 000000000000011A    sd    s0, 0(sp)    s11: 0000000000000000
                                <_Thread_Handler+0x50>
                                <Init+0x2>

grmon3> cont

hello, world

Forced into debug mode
0x0000c2ba: 9002 ebreak <_CPU_Fatal_halt+36>

grmon3>

```

Alternatively you can run GRMON with the `-gdb` command line option and then attach a GDB session to it.

5.6. RISC-V and NOEL-V integration with RTEMS

5.6.1. CSRs

RTEMS RISC-V executes in machine privilege mode only. The following is the set of CSRs which are accessed by the kernel:

- `mcause`
- `mepc`
- `mie`
- `mstatus`
- `mtvec`

5.6.2. Clock tick

`mtime` is used for the RTEMS kernel clock service. It relies on the core local interrupt controller (`clint`).

Note that an RTEMS application can chose to not use the kernel clock service, in which case the the `mtime` interrupt will not be enabled.

5.6.3. Exceptions

The only RISC-V exceptions handled by RTEMS is the `mtime` interrupt exception and external interrupts. All other exceptions (interrupt and non-interrupt) will result in a kernel fatal. The fatal handler will print the current processor state and then terminate execution.

Terminating execution is performed on NOEL-V by executing a `ebreak`.

5.6.4. NOEL-V BSP variants

The NOEL-V RTEMS BSP variants are similar to the RTEMS mainline BSP variants for RISC-V (`rv64imac`, etc) available in the kernel source tree directory `bsps/riscv/riscv/config`.

The full list of BSP variants provided with the tool chain is:

- `noel32i`
- `noel32im`
- `noel32imafd`
- `noel32imafd_smp`
- `noel32ima_smp`
- `noel64im`
- `noel64imafd`
- `noel64imafd_smp`
- `noel64ima_smp`

BSP variants suffixed with `_smp` have SMP enabled in the kernel.

5.6.5. Console driver

NOEL-V BSP variants include support for the GRLIB APBUART device which is used as RTEMS console. The GRLIB driver `apbuart_termios.c` is used. That is, the NOEL-V BSP and the LEON BSP:s use the same console driver. Polling mode is used by default and the kernel can optionally be configured for interrupt console UART.

5.6.6. Memory layout

All NOEL-V RTEMS BSP variants link the full application to RAM. The link address is the first address of RAM: `0x00000000`. ROM is not used. MMU or PMP is not used by RTEMS.

5.6.7. Work area

The NOEL-V RTEMS BSP variants tries to detect the amount of RAM and sizing of the workspace (heap) at run-time. This is done by investigating the stack pointer (`sp`) at entry to kernel.

- If `sp` equals 0 at entry to the kernel, then the BSP assumes that a total of 12 MiB RAM is available.
- If `sp` is *not* equal to 0 at entry to the kernel, then the BSP assumes that `sp` points to the top of RAM.

In both cases, the workspace (heap) is configured to use all RAM space ranging from end of the image to the end of RAM. `sp` is normally initialized by GRMON when using the `run` command.

5.7. Device tree

5.7.1. Background

RTEMS relies on a device tree description of the target system to operate. It is used for locating peripheral devices and other hardware configuration. On entry to the kernel, RTEMS assumes that a pointer to the device tree is available in register `a1`. The RTEMS init code copies the device tree from the location pointed to by `a1` to a private buffer in RAM where it is later parsed during device discovery.

When building an RTEMS application with `rtems-noel-1.0.4`, a device tree is *not* included in the link image. The benefit of this is that the same application binary can be used on different systems.

5.7.2. GRMON

GRMON is responsible for preparing the device tree binary file (`.dtb`) in RAM and pointing to it with `a1`.

Preparing and defining the device tree with GRMON is easiest done using the `dtb` command.

Then use the command `run` as normal to start an RTEMS application, or any other application expecting a device tree:

Example 5.2. load and run a RAM image which expects a device tree

```
grmon3> dtb noel-xilinx-keu105.dtb
grmon3> load myprogram.elf
grmon3> run
```

5.7.2.1. Details

The following describes how to manually prepare GRMON and the processor for executing an RTEMS application. It replicates the steps taken by the `run` command after it has been patched.

-
- The below procedure may change or may not be needed in future versions of GRMON or the RTEMS BSP.
-

1. Use the device tree compiler (`dtc`) to generate a device tree blob (`.dtb`) from a device tree source file (`.`).

```
$ dtc board.dts > board.dtb
```

2. Tell GRMON about the the device tree blob `.dtb` file with the `dtb` command.

- ```
grmon3> dtb the.dtb
```
3. Load the application ELF file.
- ```
grmon3> load hello.exe
```
4. Start execution with the GRMON command **run**.
- ```
grmon3> run
```

## 5.8. Compiler options

The build examples above use Makefile fragments available in the tool chain installation directory and is provided by the RTEMS kernel. An overview of this is given in the text file `rtems-noel-1.0.4/kernel/share/rtems5/make/README`.

All GCC compiler options are described in the GCC User's Manual. Some of the commonly used options are repeated below:

*Table 5.1. Common GCC options for rtems-noel*

|                                      |                                                                      |
|--------------------------------------|----------------------------------------------------------------------|
| <code>-g</code>                      | generate debugging information - must be used for debugging with GDB |
| <code>-msoft-float</code>            | emulate floating-point - must be used if no FPU exists in the system |
| <code>-march=rv64ima</code>          | generate code with mul/div and atomic instructions                   |
| <code>-O2</code> or <code>-O3</code> | optimize code maximum performance and minimal code size              |

## 5.9. Building the kernel

The source code for the RTEMS NOEL-V BSPs is available in the archive named `rtems-noel-1.0.4-src.tar.bz2`.

To build the kernel, first extract the NOEL-V RTEMS kernel source archive, and then use the following commands:

*Example 5.3.*

```
export THE_KERNELPREFIX=/opt/my-rtems-noel

cd <kernel-source-dir>
./bootstrap
mkdir -p build
cd build
../configure \
 --prefix=$THE_KERNELPREFIX \
 --target=riscv-rtems5 \
 --enable-smp \
 --enable-tests \
 --enable-posix=yes \
 --enable-rtemsbsp="noel32imafd_smp noel64imafd_smp"
make -j 4
make install
```

### 5.9.1. RTEMS test suite

Giving the kernel configure option `--enable-tests` will build the RTEMS kernel test suite, consisting of over 600 tests, together with the kernel. Most tests run correctly on NOEL-V. Frontgrade Gaisler is currently analyzing if failing tests can be explained by general RTEMS issues, RISC-V issues in RTEMS, or because of the NOEL-V integration.

## 5.10. Building the tool chain

The host tools can be built using the `rtems-source-builder`, as described at [RD-4]. A git patch file is included in the binary distribution which adds additional multilibs. `rtems-noel` tools were built using this patch applied on top of `rtems-source-builder`. The commit hash is specified in the README of the binary tool chain distribution.

An example on how to build the tool chain is provided below.

*Example 5.4.*

```
export THE_PREFIX=/opt/my-rtems-noel
```

```
export THE_RSB_REPO="git://git.rtems.org/rtems-source-builder.git"
export THE_RSB_COMMIT=5.1
export THE_RSB_PATCHES=/opt/rtems-noel-1.0.4/0001-noel-multilibs-for-gcc-9.3.0.patch

git clone $THE_RSB_REPO rsb

pushd rsb
git checkout -b noel $THE_RSB_COMMIT
git apply $THE_RSB_PATCHES --check
git am $THE_RSB_PATCHES
popd

pushd rsb/rtems
../source-builder/sb-set-builder --prefix=$THE_PREFIX 5/rtems-riscv
popd
```

## 6. Bare-metal cross-compiler

### 6.1. Overview

The Bare C Cross-Compiler (NCC) is a GNU-based cross-compilation system for NOEL-V processors. It allows cross-compilation of C and C++ single-threaded applications. This section gives the reader a brief introduction on how to use NCC together with the NOEL-XCKU-EX design. It will be demonstrated how to build an example program and run it on the NOEL-XCKU-EX using GRMON.

The NCC toolchain includes the GNU C/C++ cross-compiler 10.2.0, GNU Binutils, Newlib embedded C library, the Bare-C run-time system with NOEL-V support and the GNU debugger (GDB). The toolchain can be downloaded from [RD-1] and is available for Linux host.

### 6.2. Installation

Extract the toolchain and add the `bin` directory to `PATH`. For example:

```
$ cd /opt
$ tar xf ncc-1.0.0-gcc.tar.bz2
$ PATH="$PATH:/opt/ncc-1.0.0-gcc/bin"
```

The rest of this chapter assumes that the toolchain has been installed and that `riscv-gaisler-elf-gcc` is available in the `PATH` environment variable.

### 6.3. Compiling with NCC

The following command shows an example of how to compile a typical *hello, world* program with NCC.

```
$ cat hello.c
#include <stdio.h>

int main(void)
{
 printf("hello, world\n");
 return 0;
}

$ riscv-gaisler-elf-gcc -O2 -g hello.c -o hello.elf
```

It creates a program with the following characteristics:

- RV64IM instruction set
- linked to address 0.
- UART, TIMER, PLIC is probed using AMBA Plug&Play.

To build the same example targeting a 32-bit NOEL-V processor, use:

```
$ riscv-gaisler-elf-gcc -march=rv32im -mabi=ilp32 -O2 -g hello.c -o hello.elf
```

### 6.4. Compiler options

All GCC options are described in the `gcc` manual. Some of the most common options are:

Table 6.1. NCC's GCC compiler relevant options

|                      |                                                                     |
|----------------------|---------------------------------------------------------------------|
| <code>-g</code>      | generate debugging information - recommended for debugging with GDB |
| <code>-march=</code> | Selects instruction set for code generation. See Section 6.5.       |
| <code>-mabi=</code>  | Select ABI.                                                         |
| <code>-O2</code>     | optimize for speed                                                  |
| <code>-Os</code>     | optimize for size                                                   |
| <code>-Og</code>     | optimize for debugging experience                                   |

### 6.5. Multilibs

The available multilibs are:

| Directory        | Options                       |
|------------------|-------------------------------|
| rv32i/ilp32      | -march=rv32i -mabi=ilp32      |
| rv32im/ilp32     | -march=rv32im -mabi=ilp32     |
| rv32ima/ilp32    | -march=rv32ima -mabi=ilp32    |
| rv32imafd/ilp32d | -march=rv32imafd -mabi=ilp32d |
| rv64ima/lp64     | -march=rv64ima -mabi=lp64     |
| rv64imafd/lp64d  | -march=rv64imafd -mabi=lp64d  |

The default multilib when (no march or mabi) is used corresponds to -march=rv64im -mabi=ilp64.

## 6.6. Running and debugging with GRMON

Once your application is compiled, connect to your NOEL-XCKU-EX with GRMON. The following log shows how to load and run an application. Note that the console output is redirected to GRMON by the use of the `-u` command line switch, so that the application standard output is forwarded to the GRMON console.

```
$ grmon -ftdi -u
GRMON3 LEON debug monitor v3.2.9 professional version

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For latest updates, go to http://www.gaisler.com/
Comments or bug-reports to support@gaisler.com
[...]

grmon3> load hello.elf
00000000 .text 23.6kB / 23.6kB [=====] 100%
00005E70 .data 2.7kB / 2.7kB [=====] 100%
Total size: 26.29kB (803.58kbit/s)
Entry point 0x00000000
Image hello.elf loaded

grmon3> run
hello, world

CPU 0: Program exited normally.
```

To debug the compiled program you can insert breakpoints, step and continue execution directly from the GRMON console. Program symbols are loaded automatically by GRMON when you load the application. An example is provided below.

```
grmon3> load hello.elf
00000000 .text 23.6kB / 23.6kB [=====] 100%
00005E70 .data 2.7kB / 2.7kB [=====] 100%
Total size: 26.29kB (806.59kbit/s)
Entry point 0x00000000
Image hello.elf loaded

grmon3> bp main
Software breakpoint 1 at <main>

grmon3> run

CPU 0: breakpoint 1 hit
0x00001928: b0102000 addi sp, sp, -16 <main+0>

grmon3> step
0x40001928: b0102000 mov 0, %i0 <main+4>

grmon3> step
0x4000192c: 11100017 sethi %hi(0x40005C00), %o0 <main+8>

grmon3> cont
hello, world

CPU 0: Program exited normally.
```

Alternatively you can run GRMON with the `-gdb` command line option and then attach a GDB session to it.



## 7. Linux

### 7.1. Overview

A Linux image can be easily created with the help of the Buildroot tool [RD-6]. It automatically builds a toolchain and includes a wide range of user selectable software packages. This chapter will show how to get started with Buildroot and how to load and execute a Linux image on hardware using GRMON.

Frontgrade Gaisler provides a BSP for NOEL-XCKU-EX which is included in the Buildroot version downloadable from <https://www.gaisler.com/NOEL-XCKU>. The Buildroot BSP contains additional driver support for Linux.

### 7.2. Step by step instructions

Download the Buildroot distribution with the NOEL-V BSP from <https://www.gaisler.com/NOEL-XCKU> and extract it.

```
tar xf noel-buildroot.tar.gz
```

Go into the directory:

```
cd noel-buildroot
```

Generate the default config:

```
make noel32_defconfig
```

or

```
make noel64_defconfig
```

You can now make any changes you want to the configuration. For example, you could include additional software packages.

```
make xconfig
```

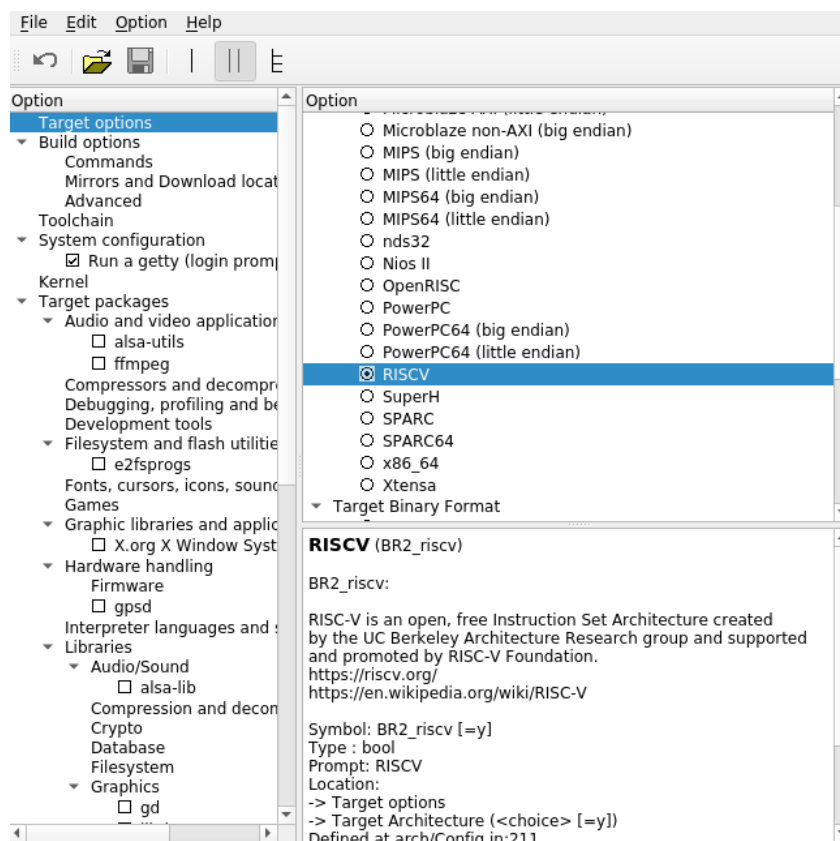


Figure 7.1. Buildroot configuration dialog

For a text only configuration dialog use:

```
make menuconfig
```

You can also configure the Linux kernel:

```
make linux-xconfig
or
make linux-menuconfig
```

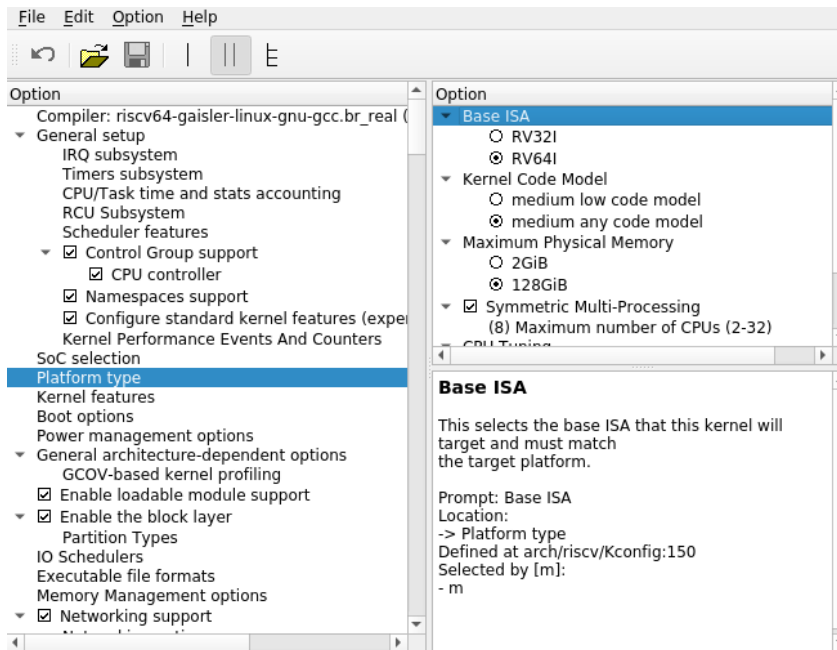


Figure 7.2. Linux kernel configuration dialog

See the Buildroot user manual for more information on how to configure your system (<https://buildroot.org>)

The image is then created by running make (this will take a while depending on the number of software packages selected):

```
make
```

The main output will be the file `output/images/fw_payload.elf` which can be loaded onto the NOEL system using GRMON.

---

The dependency handling for the OpenSBI package is not working correctly. If the image does not start or does not include recent changes to the configuration, try deleting the `output/build/opensbi-*` directory and rebuild the image.

---

Start grmon with `-u -nb` to forward the UART output and not break on page faults. Then load the image:

```
grmon3> load output/images/fw_payload.elf
40000000 .text 58.5kB / 58.5kB [=====] 100%
4000F000 .rodata 2.9kB / 2.9kB [=====] 100%
40010000 .data 512B [=====] 100%
40200000 .payload 12.7MB / 12.7MB [=====] 100%
Total size: 12.80MB (97.78Mbit/s)
Entry point 0x40000000
Image noelv-buildroot/output/images/fw_payload.elf loaded
```

Load the DTB using the `dtb` command:

```
grmon3> dtb noel-xilinx-kcu105.dtb
DTB will be loaded to the stack
```

Start the image using the run command:

```
grmon3> run
```

```
OpensBI v0.8
```



```
Platform Name : noel-xcku-ex4
Platform Features : timer,mfdeleg
Platform HART Count : 4
Boot HART ID : 0
Boot HART ISA : rv64imafdcsu
BOOT HART Features : pmp,scouteren,mcounteren
BOOT HART PMP Count : 16
Firmware Base : 0x0
Firmware Size : 144 KB
Runtime SBI Version : 0.2
```

```
MIDELEG : 0x0000000000000222
MEDELEG : 0x000000000000b109
[0.000000] Linux version 5.10.25 (@0cae9dcldffa) (riscv64-gaisler-linux-gnu-gcc.br_real (Buildroot 2020.08-3286-g4cec7096
[0.000000] OF: fdt: Ignoring memory range 0x0 - 0x200000
[0.000000] earlycon: sbi0 at I/O port 0x0 (options '')
[0.000000] printk: bootconsole [sbi0] enabled
[0.000000] Zone ranges:
[0.000000] DMA32 [mem 0x000000000200000-0x000000003fffffff]
[0.000000] Normal empty
[0.000000] Movable zone start for each node
[0.000000] Early memory node ranges
[0.000000] node 0: [mem 0x0000000000200000-0x000000003fffffff]
[0.000000] Initmem setup node 0 [mem 0x000000000200000-0x000000003fffffff]
[0.000000] software IO TLB: mapped [mem 0x0000000003b1fb000-0x0000000003f1fb000] (64MB)
[0.000000] SBI specification v0.2 detected
[0.000000] SBI implementation ID=0x1 Version=0x8
[0.000000] SBI v0.2 TIME extension detected
[0.000000] SBI v0.2 IPI extension detected
[0.000000] SBI v0.2 RFENCE extension detected
[0.000000] SBI v0.2 HSM extension detected
[0.000000] riscv: ISA extensions adfim
[0.000000] riscv: ELF capabilities adfim
[0.000000] percpu: Embedded 17 pages/cpu s32360 r8192 d29080 u69632
[0.000000] Built 1 zonelists, mobility grouping on. Total pages: 258055
[0.000000] Kernel command line: earlycon=sbi console=ttyGR0,115200
[0.000000] Dentry cache hash table entries: 131072 (order: 8, 1048576 bytes, linear)
[0.000000] Inode-cache hash table entries: 65536 (order: 7, 524288 bytes, linear)
[0.000000] Sorting __ex_table...
[0.000000] mem auto-init: stack:off, heap alloc:off, heap free:off
[0.000000] Memory: 934504K/1046528K available (9844K kernel code, 4297K rwddata, 4096K rodata, 243K init, 346K bss, 11202
[0.000000] Virtual kernel memory layout:
[0.000000] fixmap : 0xfffffffcefee00000 - 0xfffffffcefff00000 (2048 kB)
[0.000000] pci io : 0xfffffffcefff00000 - 0xfffffffcf00000000 (16 MB)
[0.000000] vmemmap : 0xfffffffcf00000000 - 0xfffffffcdfffffff (4095 MB)
[0.000000] vmlalloc : 0xfffffffcd00000000 - 0xfffffffdffffffff (65535 MB)
[0.000000] lowmem : 0xfffffffde00000000 - 0xfffffffef03fe0000 (1022 MB)
[0.000000] SLUB: HWalign=64, Order=0-3, MinObjects=0, CPUs=4, Nodes=1
[0.000000] rcu: Hierarchical RCU implementation.
[0.000000] rcu: RCU restricting CPUs from NR_CPUS=8 to nr_cpu_ids=4.
[0.000000] rcu: RCU debug extended QS entry/exit.
[0.000000] Tracing variant of Tasks RCU enabled.
[0.000000] rcu: RCU calculated value of scheduler-enlistment delay is 25 jiffies.
[0.000000] rcu: Adjusting geometry for rcu_fanout_leaf=16, nr_cpu_ids=4
[0.000000] NR_IRQS: 64, nr_irqs: 64, preallocated irq: 0
[0.000000] riscv-intc: 64 local interrupts mapped
[0.000000] plic: interrupt-controller@f8000000: mapped 31 interrupts with 4 handlers for 16 contexts.
[0.000000] random: get_random_bytes called from start_kernel+0x388/0x528 with crng_init=0
[0.000000] riscv_timer_init_dt: Registering clocksource cpuid [0] hartid [0]
[0.000000] clocksource: riscv_clocksource: mask: 0xffffffffffffffff max_cycles: 0xb8812736b, max_idle_ns: 440795202655 ns
[0.000088] sched_clock: 64 bits at 50MHz, resolution 20ns, wraps every 4398046511100ns
[0.004232] Console: colour dummy device 80x25
[0.006201] Calibrating delay loop (skipped), value calculated using timer frequency.. 100.00 BogoMIPS (lpj=200000)
[0.010085] pid_max: default: 32768 minimum: 301
[0.013665] Mount-cache hash table entries: 2048 (order: 2, 16384 bytes, linear)
[0.016578] Mountpoint-cache hash table entries: 2048 (order: 2, 16384 bytes, linear)
[0.042477] rcu: Hierarchical SRCU implementation.
[0.053153] smp: Bringing up secondary CPUs ...
[0.087982] smp: Brought up 1 node, 4 CPUs
[0.099642] devtmpfs: initialized
[0.120315] clocksource: jiffies: mask: 0xffffffff max_cycles: 0xffffffff, max_idle_ns: 7645041785100000 ns
```

```
[0.124252] futex hash table entries: 1024 (order: 4, 65536 bytes, linear)
[0.135249] NET: Registered protocol family 16
[0.383759] vgaarb: loaded
[0.390060] SCSI subsystem initialized
[0.399045] usbcore: registered new interface driver usbfs
[0.401965] usbcore: registered new interface driver hub
[0.404588] usbcore: registered new device driver usb
[0.420272] clocksource: Switched to clocksource riscv_clocksource
[0.593782] NET: Registered protocol family 2
[0.604431] tcp_listen_portaddr_hash hash table entries: 512 (order: 2, 20480 bytes, linear)
[0.608316] TCP established hash table entries: 8192 (order: 4, 65536 bytes, linear)
[0.612508] TCP bind hash table entries: 8192 (order: 6, 262144 bytes, linear)
[0.620885] TCP: Hash tables configured (established 8192 bind 8192)
[0.627483] UDP hash table entries: 512 (order: 3, 49152 bytes, linear)
[0.631704] UDP-Lite hash table entries: 512 (order: 3, 49152 bytes, linear)
[0.638468] NET: Registered protocol family 1
[0.651689] RPC: Registered named UNIX socket transport module.
[0.654220] RPC: Registered udp transport module.
[0.657014] RPC: Registered tcp transport module.
[0.659604] RPC: Registered tcp NFSv4.1 backchannel transport module.
[0.662208] PCI: CLS 0 bytes, default 64
[7.384815] workingset: timestamp_bits=62 max_order=18 bucket_order=0
[7.514220] NFS: Registering the id_resolver key type
[7.516526] Key type id_resolver registered
[7.517905] Key type id_legacy registered
[7.521251] nfs4filelayout_init: NFSv4 File Layout Driver Registering...
[7.526503] fuse: init (API version 7.32)
[7.531432] 9p: Installing v9fs 9p2000 file system support
[7.538908] NET: Registered protocol family 38
[7.541328] Block layer SCSI generic (bsg) driver version 0.4 loaded (major 251)
[7.543794] io scheduler mq-deadline registered
[7.545614] io scheduler kyber registered
[8.568597] Serial: 8250/16550 driver, 4 ports, IRQ sharing disabled
[8.585747] Serial: GRLIB APBUART driver
[8.589558] fc001000.uart: ttyGR0 at MMIO 0xfc001000 (irq = 2, base_baud = 6250000) is a GRLIB/APBUART
[8.593800] printk: console [ttyGR0] enabled
[8.593800] printk: console [ttyGR0] enabled
[8.598150] printk: bootconsole [sbi0] disabled
[8.598150] printk: bootconsole [sbi0] disabled
[8.606431] grlib-apbuart at 0xfc001000, irq 2
[8.617301] [drm] radeon kernel modesetting enabled.
[8.804665] loop: module loaded
[8.819065] libphy: Fixed MDIO Bus: probed
[8.832895] vcan: Virtual CAN interface driver
[8.836297] CAN device driver interface
[9.038755] libphy: greth-mdio: probed
[12.101012] el1000e: Intel(R) PRO/1000 Network Driver
[12.160500] el1000e: Copyright(c) 1999 - 2015 Intel Corporation.
[12.171283] ehci_hcd: USB 2.0 'Enhanced' Host Controller (EHCI) Driver
[12.180419] ehci-pci: EHCI PCI platform driver
[12.188829] ehci-platform: EHCI generic platform driver
[12.193589] ohci_hcd: USB 1.1 'Open' Host Controller (OHCI) Driver
[12.198158] ohci-pci: OHCI PCI platform driver
[12.201784] ohci-platform: OHCI generic platform driver
[12.211752] usbcore: registered new interface driver uas
[12.217027] usbcore: registered new interface driver usb-storage
[12.223879] mousedev: PS/2 mouse device common for all mice
[12.236438] usbcore: registered new interface driver usbhid
[12.240478] usbhid: USB HID core driver
[12.254464] NET: Registered protocol family 10
[12.275687] Segment Routing with IPv6
[12.279385] sit: IPv6, IPv4 and MPLS over IPv4 tunneling driver
[12.293971] NET: Registered protocol family 17
[12.297454] can: controller area network core
[12.302364] NET: Registered protocol family 29
[12.305670] can: raw protocol
[12.307598] can: broadcast manager protocol
[12.310633] can: netlink gateway - max_hops=1
[12.318451] 9pnet: Installing 9P2000 support
[12.322446] Key type dns_resolver registered
[12.327778] debug_vm_pgtable: [debug_vm_pgtable]: Validating architecture page table helpers
[12.353613] Freeing unused kernel memory: 240K
[12.382397] Run /init as init process
[14.247683] random: dd: uninitialized urandom read (512 bytes read)
[17.992829] random: crng init done
Starting syslogd: OK
Starting klogd: OK
Running sysctl: OK
Saving random seed: OK
Starting network: OK
Starting sshd: OK

Welcome to Buildroot
buildroot login:
```

You can now log into the system using `root` as username.

## 8. RTEMS Example applications

This section describes examples included in the distribution directory named `examples`.

### 8.1. Basic examples

To build an example, enter the source directory and issue `make`.

*Example 8.1.*

```
$ cd /opt/rtems-noel-1.0.4/examples/hello
$ make
```

Load and run the examples as described in Section 5.5.

Most of the examples described below use Make script fragments available in the tool chain installation directory and is provided by the RTEMS kernel. An overview of this is given in the text file `rtems-noel-1.0.4/kernel/share/rtems5/make/README`.

#### 8.1.1. hello

Prints `hello, world` to the console. It can be used as a minimal starting point for custom applications.

*Example 8.2.*

```
$ cd /opt/rtems-noel-1.0.4/examples/hello
$ make
[...]
$ grmon -digilent -u
[...]
grmon3> dtb noel-xilinx-kcul05.dtb
grmon3> load hello.exe
grmon3> run

hello, world
```

#### 8.1.2. tasks

Demonstrates the use of multiple tasks and the RTEMS directive `rtems_clock_get_tod()`.

*Example 8.3.*

```
grmon3> run

*** CLOCK TICK TEST ***
TA1 - rtems_clock_get_tod - 09:00:00 12/31/1988
TA2 - rtems_clock_get_tod - 09:00:00 12/31/1988
TA3 - rtems_clock_get_tod - 09:00:00 12/31/1988
TA1 - rtems_clock_get_tod - 09:00:04 12/31/1988
TA2 - rtems_clock_get_tod - 09:00:09 12/31/1988
TA1 - rtems_clock_get_tod - 09:00:09 12/31/1988
TA3 - rtems_clock_get_tod - 09:00:14 12/31/1988
TA1 - rtems_clock_get_tod - 09:00:14 12/31/1988
TA2 - rtems_clock_get_tod - 09:00:19 12/31/1988
TA1 - rtems_clock_get_tod - 09:00:19 12/31/1988
```

#### 8.1.3. dhrystone

This directory contains the *Dhrystone* benchmark source code and Make script.

#### 8.1.4. coremark

The *CoreMark* benchmark program from EEMBC. See the file `coremark/README.NOEL-V` for information on how to set the build parameters.

Build for NOEL-V by entering the `coremark` directory and run the script named `build.sh`:

*Example 8.4.*

```
$./build.sh
```

```
riscv-rtems5-gcc [...]
Link performed along with compile
md5sum -c coremark.md5
core_list_join.c: OK
core_main.c: OK
core_matrix.c: OK
core_state.c: OK
core_util.c: OK
coremark.h: OK
```

The output binary is named `coremark.exe`.

### 8.1.5. demo

An interactive terminal application which can toggle LEDs and display run-time information.

The following are some of the commands available in the `examples/demo` application:

- **top**: list the tasks
- **toggled N**: toggle LED N (0,1,2)
- **help**: list all available commands

See the file `demo/README` for more details.

#### Example 8.5.

```
grmon3> run

Hint: Test the commands 'toggled' and 'top'

RTEMS Shell on /dev/console. Use 'help' to list commands.
SHLL [/] # toggled
toggled: [0|1|2]
SHLL [/] # toggled 0
Toggling LED0
SHLL [/] # toggled 2
Toggling LED2
SHLL [/] # task
ID NAME SHED PRI STATE MODES EVENTS WAITINFO

0a010001 UI1 UPD 1 EV P:T:nA NONE
0a010002 JOB0 UPD 120 READY P:T:nA NONE
0a010003 JOB1 UPD 140 TIME P:T:nA NONE
0a010004 SHLL UPD 100 READY P:T:nA NONE
SHLL [/] # top
 ENTER:Exit SPACE:Refresh S:Scroll A:All <>:Order +/-:Lines

Uptime: 1m44.420027 Period: 3.620000
Tasks: 6 Load Average: 75.699% Load: 77.922% Idle: 22.077%
Mem: Wksp: 24K free 80K used Heap: 239M free 10K used 88K stack

ID | NAME | RPRI | CPRI | TIME | TOTAL | CURRENT

0x0a010002 | JOB0 | 120 | 120 | 45.178679 | 43.266 | 41.197
0x09010001 | IDLE | 255 | 255 | 25.374620 | 24.300 | 22.077
0x0a010001 | UI1 | 1 | 1 | 0.033000 | 0.031 | 0.000
0x0a010003 | JOB1 | 140 | 140 | 21.788981 | 20.866 | 19.396
0x0a010005 | CPlt | 100 | 100 | 9.936269 | 9.515 | 17.218
0x0a010004 | SHLL | 100 | 100 | 2.108507 | 2.019 | 0.109
```

### 8.1.6. Creating a custom application

The simplest way to create a custom application is to copy the `hello` directory used in the example above and modify the source code. New source code files can be added to the `Makefile` variable `CSRCS`.

## 8.2. Driver manager examples

### 8.2.1. Introduction

The directory `examples/drvmgr` contains RTEMS sample applications demonstrating how to use the RTEMS driver manager together with NOEL-V. The driver manager is compatible with 32-bit and 64-bit NOEL-V systems.

The driver manager is a device driver API software abstraction which allows developing peripheral drivers independent of bus attachment, host controller and CPU architecture. This abstraction allows sharing the same driv-

er implementation for GRLIB peripheral among the LEON 32-bit architecture, NOEL-V 32-bit architecture and NOEL-V 64-bit architecture.

At the time of writing, the current driver manager device driver implementations are being adapted to the NOEL-V systems and is progressing together with GRLIB hardware updates for endian and bus widths.

The following driver manager device drivers are fully supported on NOEL-V:

- GRGPIO
- GPTIMER
- AHBSTAT
- GRETH (32-bit NOEL-V)

### 8.2.2. Requirements

The NOEL-V RTEMS distribution 1.0.4 is required and **riscv-rtems5-gcc** should be available in PATH.

### 8.2.3. Build

To build all examples for all targets, use:

```
make
```

The example binaries will be placed inside the `bin` directory.

### 8.2.4. Targets

Examples will be built automatically for the following BSP variants:

- Single processor BSP variants
  - noel32i
  - noel32im
  - noel32imafd
  - noel64im
  - noel64imafd
- Symmetric multiprocessor BSP variants:
  - noel32imafd\_smp
  - noel32ima\_smp
  - noel64imafd\_smp
  - noel64ima\_smp

Individual BSP:s can be selected by setting the `BSPS` Make variable, for example:

```
make BSPS="noel32imafd noel32im"
```

Individual examples can be built by giving the build target on the command line:

```
make rtems-gpio
```

The executables will be stored in the root `samples` directory. When building individual examples it is possible to control the behaviour by setting the following variables.

```
CFLAGS - Override common compilation flags
CPUFLAGS - Override the hardware specific compilation flags
```

Most of the samples include `config.c` which configures drivers and help setting up networking. Network interfaces are assigned a MAC and IP address according to `networkconfig.h`.

### 8.2.5. Comments

`rtems-cdtest` is a C++ application that tests exception handling.

`rtems-ttcp` is a network test program. It implements the receiver part of the TTCP test program. The transmission part would typically execution on your host machine.



*rtems-shell* is an demonstraion program for the RTEMS shell. Type `help` at the prompt to see the available commands.

`config.c` onfigures driver resources, initializes the Driver Manager and BSP Networking Stack. `config_*.c` is the subsystem configurations.

### **8.2.6. Limitations**

The RTEMS TCP/IP network stack provided is considered experimental for 64-bit NOEL-V.

## 9. Support

For support contact the Frontgrade Gaisler support team at [support@gaisler.com](mailto:support@gaisler.com).

When contacting support, please identify yourself in full, including company affiliation and site name and address. Please identify exactly what product that is used, specifying if it is an IP core (with full name of the library distribution archive file), component, software version, compiler version, operating system version, debug tool version, simulator tool version, board version, etc.

There is also an open forum available at <https://grib.community>.

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