FH University of Applied Sciences TECHNIKUM WIEN

MASTER THESIS

Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering at the University of Applied Sciences Technikum Wien - Degree Program Mechatronics/Robotics

Virtualisierung eines Echtzeit-Betriebssystems zur Steuerung eines Roboters mit Schwerpunkt auf die Einhaltung der Echtzeit

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Wien, June 3, 2024

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Kurzfassung

Erstellung einer Echtzeit-Robotersteuerungsplattform unter Verwendung von Salamander OS, Xenomai, QEMU und PCV-521 in der Yocto-Umgebung. Die Plattform basiert auf Salamander OS und nutzt Xenomai für Echtzeit- Funktionen. Dazu muss im ersten Schritt die Virtualisierungsplattform evaluiert werden. (QEMU, Hyper-V, Virtual Box, etc.) Als weiterer Schritt folgt die Anbindung eines Roboters über eine VARAN-Bus Schnittstelle. Das gesamte System wird in der Yocto-Umgebung erstellt und konfiguriert. Das Hauptziel der Arbeit ist es, herauszufinden, wie die Integration von Echtzeit-Funktionen und effizienten Kommunikationssystemen in eine Robotersteuerungsplattform die Reaktionszeit und Zuverlässigkeit von Roboteranwendungen verbessern kann

Schlagworte: Schlagwort1, Schlagwort2, Schlagwort3, Schlagwort4

Abstract

Sections 4.1 and 4.2 demonstrate the inital real-time latency values gathered for bare metal and virtualisation.

Keywords: Echtzeit, Virtualisierung, Xenomai, VARAN

Contents

1 Introduction

In today's industrial production and automation, robot systems are well established and of crucial importance. Robots must react to their environment and perform time-critical tasks within strict time constraints. Delays or errors can have catastrophic consequences in some cases. Traditional operating systems, such as Windows or Linux, are often not suitable for these types of real-time requirements as they cannot guarantee deterministic execution times. Therefore, real-time operating systems are required that are specifically designed to react to events within fixed time limits and prioritise the execution of high-priority processes.

The core component of an RTOS that enables real-time capabilities is the kernel. The kernel is responsible for managing system resources, scheduling tasks, and ensuring deterministic behavior. It employs preemptive scheduling mechanisms to allow high-priority tasks to preempt lower-priority tasks, ensuring that time-critical tasks are not delayed. The kernel also implements priority-based scheduling algorithms, such as Rate Monotonic Scheduling (RMS) or Earliest Deadline First (EDF), to schedule tasks based on their priorities and timing constraints. Additionally, RTOS kernels are designed to minimize interrupt latency, which is crucial for real-time applications that require immediate response to external events.

In these RTOS systems, task scheduling is based on so-called priority-based preemptive scheduling. Each task in a software application is assigned a priority. A higher priority means that a faster response is required. Preemptive task scheduling ensures a very fast response. Preemptive means that the scheduler can stop a currently running task at any point if it recognizes that another task needs to be executed immediately. The basic rule on which priority-based preemptive scheduling is based is that the task with the highest priority that is ready to run is always the task that must be executed. So if both a task with a lower priority and a task with a higher priority are ready to run, the scheduler ensures that the task with the higher priority runs first. The lower priority task is only executed once the higher priority task has been processed. Real-time systems are usually categorized as either soft or hard real-time systems. The difference lies exclusively in the consequences of a violation of the time limits.

Hard real-time is when the system stops operating if a deadline is missed, which can have catastrophic consequences. Soft real-time exists when a system continues to function even if it cannot perform the tasks within a specified time. If the system has missed the deadline, this has no critical consequences. The system continues to run, although it does so with undesirably lower output quality.

1.1 Application Context

This master's thesis was written at SIGMATEK GmbH & Co KG [1]. SIGMATEK uses its own customized Linux distribution, namely Salamander 4, to be run on their self-manufactured CPUs. Salamander 4 system employs hard real-time with Xenomai 3 and requires a worst latency value between 20 and 50 µs. The goal is to virtualize Salamander 4 and approach the performance of bare metal. Salamander 4 is built with Yocto and virtualized through QEMU/KVM. The details of this operating system are explained in chapter 3.

1.2 State of the art

1.3 Problem and task definition

1.4 Objective

The main objective of this work is to create a real-time robot control platform that integrates Salamander OS, Xenomai, QEMU and PCV-521 in the Yocto environment.

2 Methodology

This section describes in detail all the theoretical concepts and boundary conditions as well as practical methods that contributed to achieving the objectives of this master's thesis.

Trace-cmd was used for tracing the Linux kernel. It can record various kernel events such as interrupts, scheduler decisions, file system activity, function calls in real time. Trace-cmd helped in getting detailed insights into system behaviour and identify reasons for latency [2].

The data that was recorded by trace-cmd was then fed into Kernelshark, which is a graphical front-end tool [3]. It visualizes the recorded kernel trace data in a readable way on an interactive timeline, which facilitated the process of identifying patterns and correlations between events. By further filtering the displayed events according to specific criteria such as processes, event types or time ranges, the latency issues were analyzed.

Real-time operating system capabilities were provided by Xenomai, which is real-time development framework that extends the Linux kernel. It enables low-latency and deterministic execution of time-critical tasks. Xenomai 3 introduces a dual-kernel approach with a real-time kernel coexisting alongside Linux. A key utility within the Xenomai suite is the latency tool, which benchmarks the timer latency - the time it takes for the kernel to respond to timer interrupts or task activations. The tool creates real-time tasks or interrupt handlers and measures the latency between expected and actual execution times [4].

The system configuration is shown in Table 1

Table 1: System configuration

CPU	13th Gen Intel(R) Core(TM) i7-13800H
Memory	2x 16GB SO-DIMM DDR5-5600 MT/s, 32GB
GPU	NVIDIA RTX A500 Laptop GPU
BIOS	Dell Version 1.12.0
OS	Ubuntu 22.04.4 LTS

Figure 1 is the output of the `lstopo` command and visualizes the hardware nodes of the system, including CPU cores, caches, memory, and I/O devices.

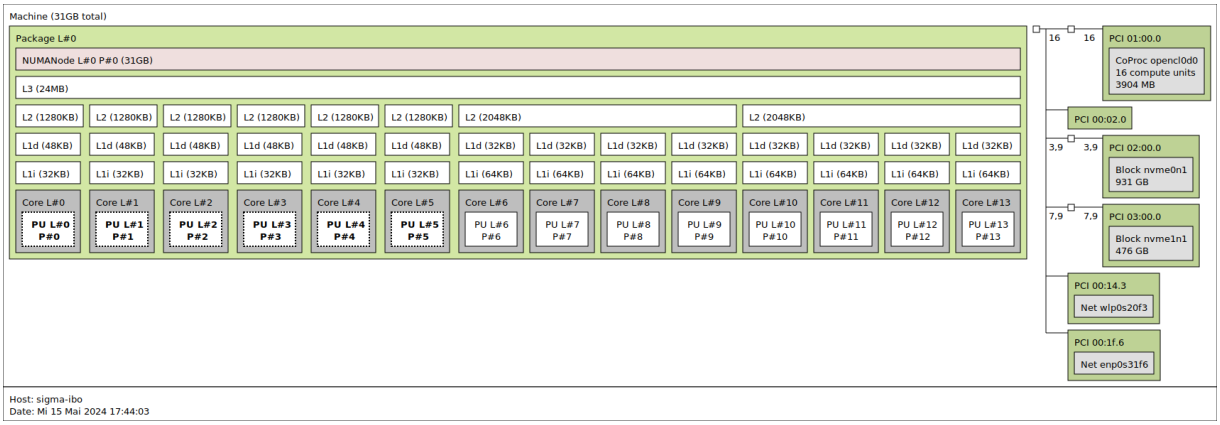

Figure 1: Hardware topology

3 Salamander 4

This chapter briefly describes the Salamander 4 operating system by SIGMATEK.

3.1 Structure

Salamander 4 is the proprietary operating system of SIGMATEK. It is based on Linux version 5.15.94 and integrates Xenomai 3.2, a real-time development environment [4]. Salamander 4 is a 64-bit system, which refers to the x86_64 architecture. The real-time behaviour is achieved through the use of Symmetric Multi-Processing (SMP) and Preemptive Scheduling (PREEMPT). In addition, it uses IRQPIPE to process interrupts in a way that meets the real-time requirements of the system. The output of the command `uname -a` can be observed in code 1.

```
1 root@sigmatek-core2:~# uname -a
2 Linux sigmatek-core2 5.15.94 #1 SMP PREEMPT IRQPIPE Tue Feb 14 18:18:05 UTC
      2023 x86_64 GNU/Linux
```

Code 1: System information

Salamander 4 is powered by SIGMATEK's CP 841 [5] and is comprised of the following software modules:

- **Operating system**: The operating system in a LASAL CPU manages the hardware and software resources of the system. It is provided in a completely PC-compatible manner, working with a standard PC BIOS.
- **Loader**: The loader is a part of the operating system that is responsible for loading programs from executables into memory, preparing them for execution and then executing them.
- **Hardware classes**: Hardware classes in LASAL represent the different types of hardware components that can be controlled by the LASAL CPU. They provide a way to organize and manage the hardware components in a modular and reusable manner. The graphical hardware editor in LASAL allows for a true-to-detail simulation of the actual hardware.
- **Application**: Applications are developed using LASAL CLASS 2 [6], a solution for automation tasks that supports object-oriented programming and design in compliance with IEC 61131-3.

The interfaces between the individual modules are indicated by an arrow in Figure 2.

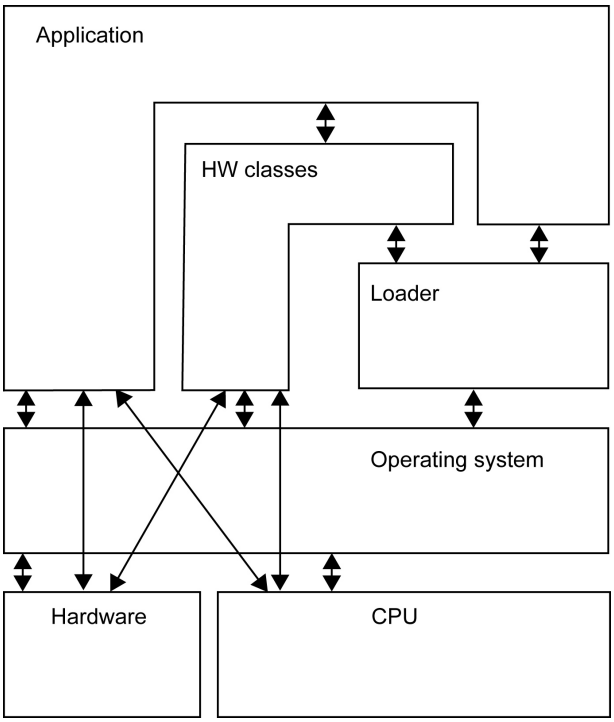

Figure 2: Structure of Salamander 4 CPU

3.2 Memory Management

For the sake of completeness, Figure 3 displays the memory management of Salamander 4. LRT stands for Lasal Runtime and creates an execution environment where applications developed using the LASAL Class 2 can run, providing defined real-time functions, data types, and other constructs tailored for real-time programming.

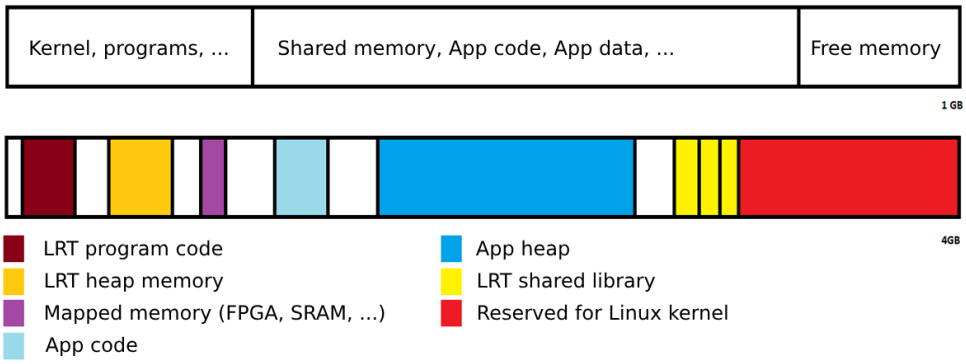

Figure 3: Memory Management

3.3 Xenomai

Xenomai 3 [4] is a real-time framework that offers two paths to real-time performance. The first approach supplements the Linux kernel with a compact real-time core dubbed Cobalt, demonstrated in Figure 4. Cobalt runs side-by-side with Linux, but it handles all time-critical activities like interrupt processing and real-time thread scheduling with higher priority than the regular kernel activities.

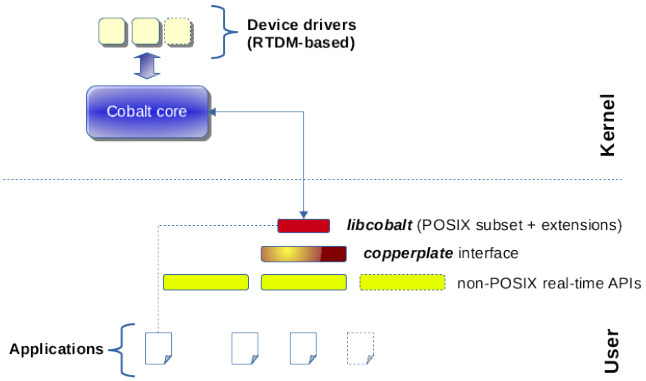

Figure 4: Xenomai Cobalt interfaces

The second approach, called Mercury and shown in Figure 5, relies on the real-time capabilities already present in the native Linux kernel. Often, applications require the PREEMPT-RT extension to augment the mainline kernel's real-time responsiveness and minimize jitter, but this isn't mandatory and depends on the application's specific requirements for responsiveness and tolerance for occasional deadline misses.

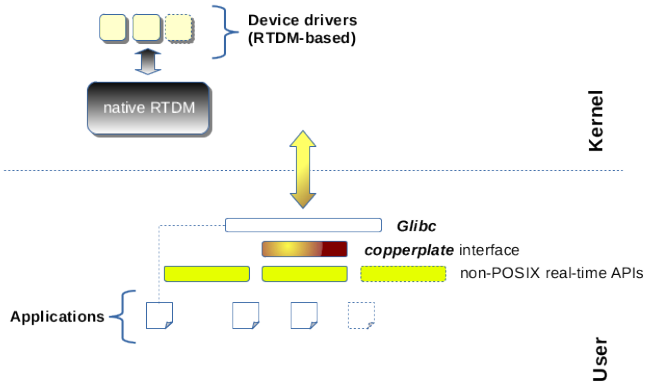

Figure 5: Xenomai Mercury interfaces

Salamander 4 uses the Cobalt real-time core with the Dovetail extension, which allows the kernel to handle real-time tasks with low latency.

4 Initial Real-Time Latency

As a starting point, initial latency values of both the bare metal and virtualization versions were measured with the latency tool of the xenomai tool suite. Salamander 4 Bare Metal refers to the proprietary hardware of SIGMATEK used to employ the custom operating system. Salamander 4 virtualisation refers to a virtual version of the Salamander 4 hardware platform, achieved through QEMU/KVM. Sections 4.1 and 4.2 specify the details of the measurements for both versions. In the further course, the aim was to bring the latency values of the virtualization closer to those of the hardware.

4.1 Salamander 4 Bare Metal

The output of the command `uname -a` for Salamander 4 bare metal is shown in code 2.

```
1 root@sigmatek-core2:~# uname -a
2 Linux sigmatek-core2 5.15.94 #1 SMP PREEMPT IRQPIPE Tue Feb 14 18:18:05 UTC
      2023 x86_64 GNU/Linux
```

Code 2: Salamander 4 bare metal system information

As a reference point, the latency program was executed on Salamander 4 bare metal for a duration of 10 minutes. The complete command used was `latency -h -s -T 600`. Figure 6 shows the gathered latency values in microseconds.

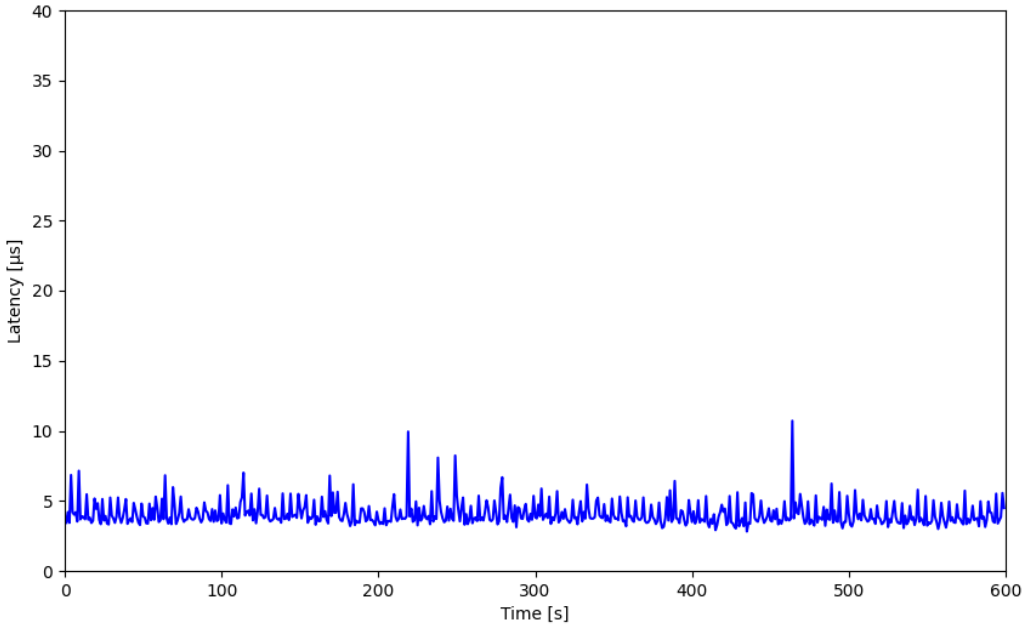

Figure 6: Latency in hardware

Figure 7 depicts the variation in latency over the course of said time.

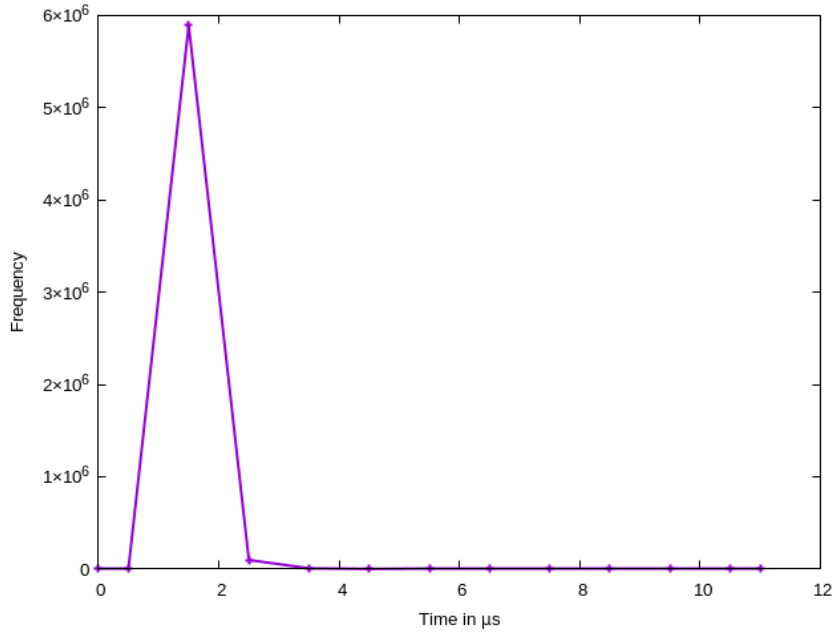

Figure 7: Variation in latency of hardware

The statistics obtained from this measurement are provided in Table 2. It gives an overview of the average, maximum, minimum latency, and the standard deviation of the latency values in microseconds.

Table 2: Latency Statistics in microseconds

Statistic	Value (in µs)
Average Latency	4.06
Maximum Latency	10.71
Minimum Latency	2.82
Standard Deviation	0.85

4.2 Salamander 4 Virtualisation

In addition to providing Salamander 4 on its own hardware, SIGMATEK has also developed a virtualised version of this operating system. It was developped using Yocto, an open source project that allows customised Linux distributions to be created for embedded systems [7]. The virtualisation runs in a QEMU environment, which is an open source tool for hardware virtualisation [8]. With the help of the script depicted in code 4, Salamander 4 is started together with the necessary hardware components in the QEMU environment. This makes it possible to run Salamander 4 on a variety of host systems, regardless of the specific hardware of the host. Upon generating the necessary files, Yocto generates a QEMU folder with the following components shown in code 3.

```
1  sigma_ibo@localhost:~/Desktop/salamander-image$ ls -1
2  bzImage
3  drive-c
4  ovmf.code.qcow2
5  qemu_def.sh
6  salamander-image-sigmatek-core2.ext4
7  stek-drive-c-image-sigmatek-core2.tar.gz
8  vmlinux
```

Code 3: Contents of QEMU folder for Salamander 4

Here is a description of the used components:

- **bzImage**: Compressed Linux kernel image, loaded by QEMU at system start.
- **ovmf.code.qcow2**: Firmware file for QEMU, enables UEFI boot process.
- **qemu_def.sh**: Shell script, starts QEMU with correct parameters to boot Salamamder 4 OS.

- **stek-drive-c-image-sigmatek-core2.tar.gz**: Archive containing files for C drive, unpacked and copied to drive-c/ directory by qemu_def.sh script.
- **drive-c**: Directory serving as C drive for QEMU system, created and filled by qemu_def.sh script.
- **salamander-image-sigmatek-core2.ext4**: Root file system for Salamander 4 OS, used as hard drive for QEMU system.
- **vmlinux**: Uncompressed Linux kernel image, typically used for debugging, contains debugging symbols not present in bzImage.

The inital QEMU script after the custom Yocto build and the starting point for this work is shown in Code 4. This script is used to start QEMU with correct parameters to boot Salamamder 4 OS. It will be adjusted in chapter 5 in order to accompany real-time performance tunings.

```
1  #!/bin/sh
2
3  if  [ ! -d drive-c/ ]; then
4          echo "Filling drive-c/"
5          mkdir drive-c/
6          tar -C drive-c/ -xf stek-drive-c-image-sigmatek-core2.tar.gz
7  fi
8
9  exec  qemu-system-x86_64 -M pc,accel=kvm -kernel ./bzImage \
10 -m 2048 -drive
       file=salamander-image-sigmatek-core2.ext4,format=raw,media=disk \
11 -append "console=ttyS0 console=tty1 root=/dev/sda rw panic=1
       sigmatek_lrt.QEMU=1 ip=dhcp rootfstype=ext4 schedstats=enable" \
12 -net nic,model=e1000,netdev=e1000 -netdev bridge,id=e1000,br=nm-bridge \
13 -fsdev local,security_model=none,id=fsdev0,path=drive-c -device
       virtio-9p-pci,id=fs0,fsdev=fsdev0,mount_tag=/mnt/drive-C \
14 -device vhost-vsock-pci,guest-cid=3,id=vsock0 \
15 -drive if=pflash,format=qcow2,file=ovmf.code.qcow2 \
16 -no-reboot -nographic
```

Code 4: QEMU script for starting Salamander 4 virtualisation

The script is run on a generic Ubuntu 22.04.4 system. The kernel version and other details are presented in Code 5, using the `uname -a` command.

```
1 root@sigmatek-core2:~# uname -a
2 Linux sigma-ibo 6.5.0-35-generic #35~22.04.1-Ubuntu SMP PREEMPT_DYNAMIC Tue
     May  7 09:00:52 UTC 2 x86_64 x86_64 x86_64 GNU/Linux
```

Code 5: Ubuntu 22.04.4 system information

Measuring the latency of the Salamander 4 virtualization with the default QEMU script in Code 4 and no further adjustments for 10 minutes, the following latency values in Figure 8 were collected.

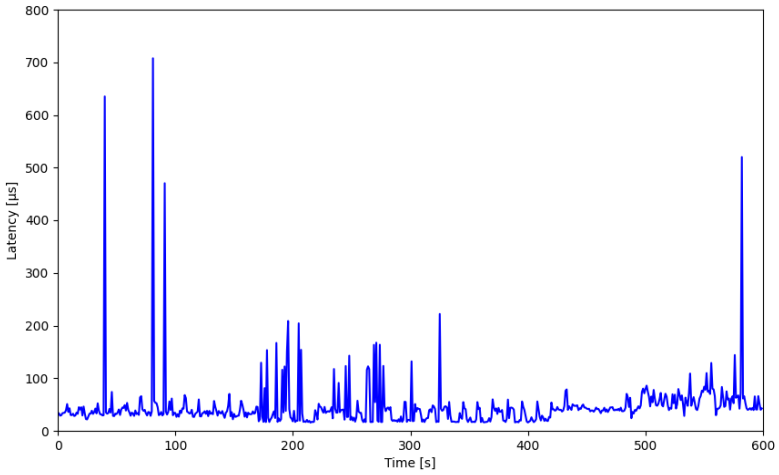

Figure 8: Latency with default settings

Figure 9 depicts the variation in latency with default settings over the course of said time.

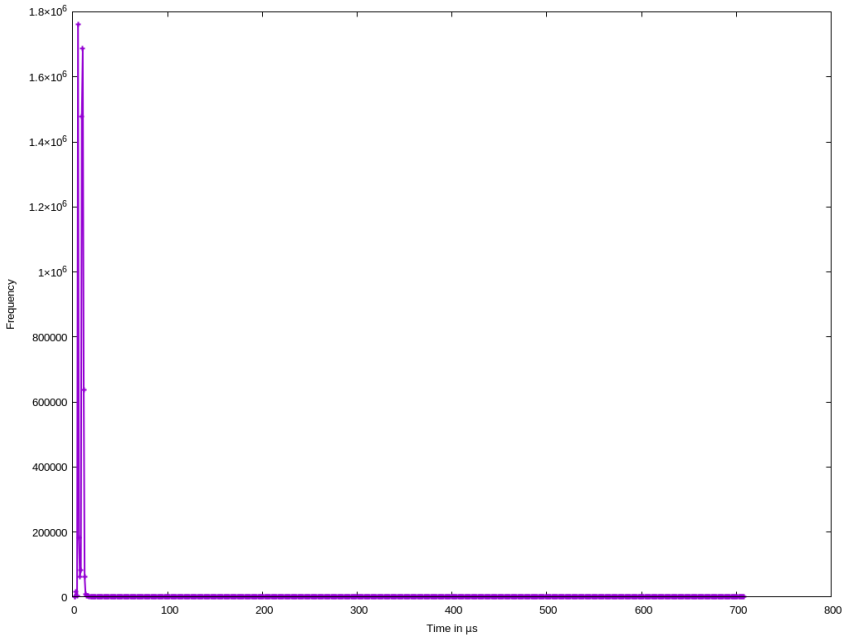

Figure 9: Variation in latency with default settings

The statistics obtained from this measurement are provided in Table 3. It gives an overview of the average, maximum, minimum latency, and the standard deviation of the latency values in microseconds.

Table 3: Latency Statistics default in microseconds

Statistic	**Value (in µs)**
Average Latency	46.22us
Maximum Latency	707.62us
Minimum Latency	15.59us
Standard Deviation	52.13us

5 Real-Time Performance Tuning

5.1 BIOS Configurations

BIOS is firmware used to perform hardware initialization during the booting process. Some BIOS settings can have a significant impact on the real-time performance of the system [2]. The configurations in Table 4 are tuned for real-time performance.

Table 4: BIOS Configurations

Option	**Status**
Hyper Threading	Disabled
Intel SpeedStep®	Disabled
Intel® Speed Shift Technology	Disabled
C States	Disabled
VT-d	Enabled

5.2 Kernel Configurations

The kernel command-line parameters [6] are shown in Code 6 below. Some of them are essential for real-time performance.

```
1       GRUB_CMDLINE_LINUX="isolcpus=4 rcu_nocbs=4 nohz_full=4
            default_hugepagesz=1G hugepagesz=1G hugepages=8 intel_iommu=on
            rdt=l3cat nmi_watchdog=0 idle=poll clocksource=tsc tsc=reliable
            noht audit=0 skew_tick=1 intel_pstate=disable intel.max_cstate=0
            intel_idle.max_cstate=0 processor.max_cstate=0
            processor_idle.max_cstate=0 nosoftlockup nohz=on no_timer_check
            nospectre_v2 spectre_v2_user=off kvm.kvmclock_periodic_sync=N
            kvm_intel.ple_gap=0 irqaffinity=0"
```

Code 6: Kernel Configuration

In the following, these settings along with their impact on system latency are briefly described.

- **isolcpus=4**: This isolates CPU 4 from the general scheduler, meaning no process will be scheduled to run on this CPU unless it is explicitly assigned.

- **rcu_nocbs=4**: Moves the RCU (Read-Copy-Update) callback handling off of CPU 4.
- **nohz_full=4**: Makes CPU 4 tickless, reducing the timer interrupts and thus can improve performance for specific applications.
- **default_hugepagesz=1G, hugepagesz=1G, hugepages=8**: Sets the default huge page size to 1GB, and reserves 8 huge pages at boot.
- **intel_iommu=on**: Enables Intel's IOMMU (Input/Output Memory Management Unit) for hardware that supports it.
- **rdt=l3cat**: Enables the L3 Cache Allocation Technology.
- **nmi_watchdog=0**: Disables the NMI watchdog, which can free up a bit of system resources.
- **idle=poll**: Changes the idle loop of the CPU to actively poll.
- **clocksource=tsc, tsc=reliable**: Sets the clocksource to TSC (Time Stamp Counter) and marks it as reliable.
- **noht**: Disables Hyper-Threading.
- **audit=0**: Disables the Linux audit system.
- **skew_tick=1**: Enables a mode to reduce timer interrupt overhead.
- **intel_pstate=disable**: Disables the intel_pstate driver.
- **intel.max_cstate=0, intel_idle.max_cstate=0, processor.max_cstate=0, processor_idle.max_cstate=0**: Disables deeper C-states, which can help reduce latency.
- **nosoftlockup**: Disables the soft lockup detector.
- **nohz=on**: Enables tickless operation system-wide.
- **no_timer_check**: Disables the check for broken timer interrupt sources.
- **nospectre_v2, spectre_v2_user=off**: Disables mitigations for the Spectre v2 vulnerability.
- **kvm.kvmclock_periodic_sync=N, kvm_intel.ple_gap=0**: These are KVM (Kernel-based Virtual Machine) related parameters.
- **irqaffinity=0**: Sets the default IRQ affinity.

5.3 Host OS Configurations

5.3.1 CPU isolation

Isolating CPUs involves removing all user-space threads and unbound kernel threads since bound kernel threads are tied to specific CPUs and hence cannot be moved. Also, modifying the `proc/irq/IRQ_NUMBER/smp_affinity` property of each Interrupt IRQ_NUMBER in the system is part of this process, as described later in section 5.3.2.

For CPU isolation, the `isolcpus` function was used to isolate a peroformance CPU from the general scheduling algorithms of the operating system. This means that the isolated CPUs will not be used for regular task scheduling, allowing them to be dedicated for the real-time specific tasks or processes. However, the isolcpus function only isolates at the user level and does not affect kernel tasks. Consequently, these kernel tasks and interrupts can still utilize the CPU [9]. Output 7 shows the user and kernel tasks that run on CPU 4. After the isolation, user tasks other than the QEMU process have been removed from running on this CPU. Only few critical kernel threads that are tied to this CPU still take CPU time.

```
1  sigma_ibo@sigma-ibo:~$ cat /sys/devices/system/cpu/isolated
2  4
3  sigma_ibo@sigma-ibo:~$ ps axHo psr,pid,lwp,args,policy,nice,rtprio |
       awk '$1 == 4'
4  4       38       38 [cpuhp/4]                    TS    0      -
5  4       39       39 [idle_inject/4]              FF    -     50
6  4       40       40 [migration/4]                FF    -     99
7  4       41       41 [ksoftirqd/4]                TS    0      -
8  4       43       43 [kworker/4:0H-events_highpr TS  -20      -
9  4      505      505 [irq/189-iwlwifi:queue_1]    FF    -     50
10 4      519      519 [irq/203-iwlwifi:exception] FF    -     50
11 4     3008     3008 [kworker/4:1H-kblockd]      TS  -20      -
12 4   177779   177779 [kworker/4:2-events]         TS    0      -
13 4   448807   448807 [kworker/4:1-events]         TS    0      -
```

Code 7: User and Kernel Tasks

5.3.2 Interrupt Requests Handling

Once the CPUs were isolated, Interrupt Requests handling was the next step. Interrupt Requests are used to send a signal to the CPU, prompting it to 'interrupt' its current task and divert its attention to another task. This allows hardware devices to communicate with the CPU through frequent context switches, which can lead to performance degradation, especially in high-performance computing or real-time scenarios. To mitigate this, the IRQs needed to be removed from the isolated CPU. This was done by manipulating a file in the `proc` filesystem, namely `/proc/irq/<IRQ>/smp_affinity`. The value in the `smp_affinity` file is a bit-mask in hexadecimal format. Each bit in this mask corresponds to a CPU in the system. The

least significant bit (LSB) on the right corresponds to the first CPU (CPU0), and the significance increases towards the left until CPU19. In a system with 14 CPUs, if every CPU was reserved for one IRQ, the value for `smp_affinity` would be 3FFF. The script in code 8 was written to check and log the distribution of Interrupt Requests across each CPU in Salamander 4.

```
#!/bin/bash
# Check if a command-line argument is provided
if [ -z "$1" ]; then
   echo "Please provide a CPU number as a command-line argument."
   exit 1
fi
# Get the CPU number from the command-line argument
CPU=$1
# Initialize an empty array to store the IRQ numbers
IRQs=()
for IRQ in /proc/irq/*; do
   if [ -f "$IRQ/smp_affinity" ]; then
      # Read the current smp_affinity
      AFFINITY=$(cat "$IRQ/smp_affinity")
      # Check if the bit for the current CPU is set
      if (( (0x$AFFINITY & (1 << CPU)) != 0 )); then
         # Add the IRQ number to the array
         IRQs+=("${IRQ#/proc/irq/}")
      fi
   fi
done
# Sort the array
IFS=$'\n' sorted=($(sort -n <<<"${IRQs[*]}"))
# Print the CPU number
echo "CPU $CPU IRQ affinity:"
# Print the sorted IRQ numbers on separate lines
for irq in "${sorted[@]}"; do
   echo "$irq"
done
```

Code 8: Check distribution of Interrupt Requests across each CPU

```
sigma_ibo@sigma-ibo:~$ ./check_smp_affinity.sh 19
CPU 19 IRQ affinity:
0
2
3
4
5
6
7
10
11
13
15
131
172
188
189
195
```

Code 9: Output of smp_affinity for CPU 19

By changing the values of the `smp_affinity` files of the respective IRQs, the assignment of IRQs was controlled so that they would not be handled by the isolated CPU. This reduced the interruptions caused by IRQs and the isolated CPUs were able to focus more on their assigned tasks.

5.5 Guest OS Configurations

```
17  #!/bin/sh
18
19  if  [ ! -d drive-c/ ]; then
20          echo "Filling drive-c/"
21          mkdir drive-c/
22          tar -C drive-c/ -xf stek-drive-c-image-sigmatek-core2.tar.gz
23  fi
24
25  exec  qemu-system-x86_64 -M pc,accel=kvm -kernel ./bzImage \
26  -m 2048 -drive
        file=salamander-image-sigmatek-core2.ext4,format=raw,media=disk \
27  -append "console=ttyS0 console=tty1 root=/dev/sda rw panic=1
        sigmatek_lrt.QEMU=1 ip=dhcp rootfstype=ext4 schedstats=enable" \
28  -net nic,model=e1000,netdev=e1000 -netdev bridge,id=e1000,br=nm-bridge \
29  -fsdev local,security_model=none,id=fsdev0,path=drive-c -device
        virtio-9p-pci,id=fs0,fsdev=fsdev0,mount_tag=/mnt/drive-C \
30  -device vhost-vsock-pci,guest-cid=3,id=vsock0 \
31  -drive if=pflash,format=qcow2,file=ovmf.code.qcow2 \
32  -no-reboot -nographic
```

Code 10: QEMU script for starting Salamander 4 virtualisation

6 KVM exit reasons

6.1 APIC_WRITE

6.2 HLT

6.3 EPT_MISCONFIG

6.4 PREEMPTION_TIMER

6.5 EXTERNAL_INTERRUPT

6.6 IO_INSTRUCTION

6.7 EOI_INDUCED

6.8 EPT_VIOLATION

6.9 PAUSE_INSTRUCTION

6.10 CPUID

6.11 MSR_READ

7 Real-Time Robotic Application

7.1 VARAN

7.2 Robotic Application

8 Results

[1] [2] [3] [4] [5] [6] [7] [8] [9] [10] [11] [12] [13] [14] [15] [16] [17] [18] [19] [20] [21] [22] [23] [24] [25] [26] [27] [28] [29] [30]

9 Discussion

10 Summary and Outlook

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List of Abbreviations

CPU Central Processing Unit

QEMU Quick Emulator

IRQ Interrupt Request

A Anhang A

B Anhang B