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Software-based methods for Operating system dependability

By

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Declaration

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Abstract

Guaranteeing correct system behaviour in modern computer systems has become essential, in particular for safety-critical computer-based systems. However all modern systems are susceptible to transient faults that can disrupt the intended operation and function of such systems. In order to evaluate the sensitivity of such systems, different methods have been developed, and among them Fault Injection is considered a valid approach widely adopted.

This document presents a fault injection tool, called Kernel-based Fault-Injection Tool Open-source (KITO), to analyze the effects of faults in memory elements containing kernel data structures belonging to a Unix-based Operating System and, in particular, elements involved in resources synchronization. This tool was evaluated in different stages of its development with different experimental analyses by performing Faults Injections in the Operating System, while the system was subject to stress from benchmark programs that use different elements of the Linux kernel. The results showed that KITO was capable of generating faults in different elements of the operating systems with limited intrusiveness, and that the data structures belonging to synchronization aspects of the kernel are susceptible to an appreciable set of possible errors ranging from performance degradation to complete system failure, thus preventing benchmark applications to perform their task.

Finally, aiming at overcoming the vulnerabilities discovered with KITO, a couple of solutions have been proposed consisting in the implementation of hardening techniques in the source code of the Linux kernel, such as *Triple Modular Redundancy* and *Error Detection And Correction* codes. An experimental fault injection analysis has been conducted to evaluate the effectiveness of the proposed solutions. Results have shown that it is possible to successfully detect and correct the noxious effects generated by single faults in the system with a limited performance overhead in kernel data structures of the Linux kernel.

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Chapter 1

Introduction

1.1 The Man Who Saved the World

On the 1st of September of 1983 a civilian flight of Korean airlines (KAL007) was shot down by a soviet Sukhoi 15 interceptor killing all 269 occupants. The flight was en route to Seoul from Anchorage, it deviated from its planned course and violated Soviet airspace twice, first at the Kamchatka Peninsula and then again at Sakhalin Island. This led to arguably one of the most tense moments of the cold war. Following the incident, the USA deployed nuclear capable Pershing II missiles in West Germany generating an atmosphere similar to the 1962 missile crisis, not even a month after this tragedy the situation would reach its apex. On the 26th September 1983, Lieutenant Colonel (LtCol.) Stanislav Petrov, was the duty officer overwatching the Oko early warning satellite system. Past midnight, the system notified of an Inter-Continental Ballistic Missile (ICBM) launched from the continental USA, heading towards the Soviet Union. LtCol. Petrov suspected that the alarm was a system malfunction and dismissed the alert given that no other system had detected the missile. In the following minutes four new ICBM launches were detected by the Oko system, and those alarms were also dismissed by LtCol. Petrov. The decision made by LtCol. Petrov was based on the assumption that a nuclear attack from the USA would be a massive assault and not only with five missiles. By dismissing these alarms and reporting the event as false alarm to higher echelons LtCol. Petrov may have prevented a nuclear war.

This event is the ultimate example of the importance of detecting and correcting failures in safety-critical computer-based applications such as an early warning and control system, in particular these system linked to the most powerful weapons ever created by man.

1.2 Modern System Dependability

The necessity of dependable systems is not only limited to weapons of mass destruction, other sectors such as automotive, railway, aircraft flight control systems and even space exploration rely in such systems. Unfortunately, these systems tend to be very complex, thus it has become very difficult to certify their correct behaviour under any conditions. There has been examples of such systems being affected by such faults. On October of 2008 the autopilot of a plane from Qantas suffered a fault that made the plane drop 1050 feet [1]: this malfunction resulted in severe injury for 11 passengers. Another example involved the Voyager 2 probe's data system back in 2010 [2]: in this example a single memory bit flip in the system that packages the data for transition to earth was responsible for the transmission of incompressible data. This problem was solved by restarting the system on board. Even systems related to the election of decision maker of entire countries have been affected by these faults. In 2003, a single bit flip in an electronic voting machine in Belgium granted 4,096 extra votes to a single electoral candidate before the error was detected and corrected [3].

These soft errors in components occur due to factors that can usually be divided between natural and man made causes. Those faults from natural causes are those which occur because of environmental phenomena, such as electromagnetic noise, high energy particles, temperature, component ageing, among others [4]. While man made faults are those caused from human interaction with the component, these interactions can be either intentional or accidental, either by human mistakes while manipulating the components, or omission of procedures, such as lack of maintenance. These soft errors can incur into different kinds of abnormal behaviours, depending of how, when and where the faults occur in the system. These faults can interfere or not, with the output of the system. For example a fault in the data used as input by a system could modify the expected output result of the operations. While, if the same fault occurs after the data was fetched, the result of the operation is not affected. Additionally, apart from inferring with the normal operation of the systems, these faults could also have a high probability of damage the system as the magnitude of the electric charges used to store information continues to decrease [4].

Nowadays, availability is strictly required for all digital systems directly linked to human safety or economic interests. Therefore, dependability of a system must be evaluated, and in order to do so, fault occurrence has to be artificially accelerated to better understand how the system reacts to faults. For this reason many methods have been developed, and among those, the most common is Fault Injection [5, 6]. Many safety standards, e.g., IEC 61508 [7], require fault injection campaigns to be performed as one of a number of software validation activities. Fault injection tools tend to modify the user applications, introducing faults in the input and stored data or the code segments of the running process as well as into the registers and memory locations it uses.

1.3 Fault Injections Methods

In order to show the variety of possible fault injections, this section introduces the different fault injection methods adopted in recent years and presents examples of such implementations. Different fault injection techniques can be analyzed according to the following characteristics [8]:

- Controllability: the ability to control the time and location of the fault injection
- Repeatability: the ability to repeat the experiments
- Reproducibility: the ability to recreate a result
- Intrusiveness: the undesired ability to impact the normal operation of the system apart from the fault injection.

1.3.1 Hardware-Implemented Fault Injection

Hardware-implemented fault injection allows to inject faults by physical means in the systems. Implementation on hardware can allow very high injection time controllability, however, can be severely lacking in terms of spatial controllability, meaning that the location where to make the fault injection can be very limited and inaccurate. The most common hardware-implemented fault injection techniques can be summarized as follows.

In *pin-level fault injection* [9], by forcing *pull ups* or *pull downs* on pins of an IC enable, it is possible to make injection of faults in the system. There are limitations to controllability, given that not all the pins are reachable in modern ICs, however, this approach presents very high reproducibility and temporal controllability.

A commonly used approach is *heavy-ion fault injection* [10], the IC under study is bombarded with heavy electrically charged isotopes. Another similar technique is *electromagnetic interference fault injection* [11], and in this method induction generators are used as means of fault injector. Both of these approaches posses negligible intrusiveness, but also negligible controllability of a particular location, therefore, reproducibility is particularly difficult to achieve.

Background debug mode fault injection (BDM) [12] exploits built-in test and debug capabilities of modern microprocessors. Given that these capabilities are provided by the supplier, the reproducibility of this technique is high, but suffers of a significant degree of intrusiveness.

The most common drawback of hardware fault injection techniques is the very high implementation cost, particularly true for heavy-ion and electromagnetic interference fault injection techniques. Furthermore, in some of these fault injection methods the risk of damaging the system under test is sometimes unavoidable. Additionally, the elapsed time to complete a fault injection campaign suffers for the need to restart the system after each experiment.

1.3.2 Simulation and Emulation Based Fault Injection

Simulation-based fault injection refers to techniques that implement computer system models to simulate faults at electrical circuit level, gate level or higher levels in IC, such as full components. Simulation provides a basic representation of the system (in particular when concerning the input and output of the system), but doesn't respect completely with all rules of the system. While *Emulation-based fault injection* is the technique that implements a computer whole system's rules and environments to allow the execution of the fault injection in the emulated models.

A typical approach is to generate tools to evaluate circuit models considering the typical soft error characteristics. As an example, [13] presents a library developed to predict single errors rates in combinational circuits, by taking into consideration typical current responses of different soft error characteristics. While in [8], a tool called MODIFI (MODel-Implemented Fault Injection) is capable to simulate faults by means of a XML defined model for Simulink while the algorithm for the fault injection uses minimal cut sets.

Other simulation-based tools, such as MEFISTO [14], implement faults by means of *saboteurs*. These saboteurs are additional or modified (*mutant*) components that replace healthy (fault free) components in a system. In the particular case of MEFISTO this evaluation is made in a VHDL environment. A similar technique is implemented in [15], where saboteurs are implemented by using commercial debugging tools from Altera. Evaluation of faults effects in state-of-the-art technologies such as quantum circuits has also been done implementing simulation based fault injection, as can be seen in [16]. This example used the implementation of saboteurs and mutants into the VHDL models of quantum circuits.

These techniques tend to be intensive in computing time given the complexity of such systems. An example of their level of complexity can be seen in DEPEND [17]. This tool provides a fault injection environment for system level dependability analysis, simulating an Unix-based Tandem Triple-Modular-Redundancy (TMR) based fault-tolerant system.

In [18] fault emulation for VLSI circuits is discussed, and the proposed FPGA emulation system allows to speed up the fault injection campaigns by taking the speed characteristics of hardware faults implementation, and the versatility of simulation based fault injection.

Finally, in [19] an emulation environment is proposed for testing of ICs in prototypal phases by means of an optimized framework.

One drawback of these systems is the confidence in the outcome of the fault in elements that are not considered in fault injection campaigns. In [20] a method to quantify the confidence in both the reported results and the estimation of the effects of unsurveyed faults in order to improve the margin of error such campaigns.

Both Simulation and emulation based fault injection techniques are remarkably advantageous in their high controllability, repeatability and reproducibility and negligible intrusiveness. Additionally, in both fault injection campaigns can be made before the prototypal stages of the system undergoing analysis. Notwithstanding, these techniques require huge amounts of computing power and time, together with the fact that these requirements increase rapidly as the complexity of the system increases.

1.3.3 Software Implemented Fault Injection

Software implemented fault injection (SWIFI) is made by stimulating the conditions that a physical fault would have in software and data, by means of faults in the CPU registers and/or memory elements. SWIFI techniques commonly implement memory bit flips, emulation of corrupt data segments or corrupt instructions in the software under test. Among these techniques the difference is commonly the adopted injection method.

FERRARI [21] implements a technique that injects faults into CPU registers, memory and bus by means of software traps. After a program reaches a certain point in its execution or by expiration of a timer, these traps are triggered; the fault injection then is made by changing the contents of registers and memory via changes in the system calls in order to emulate corrupt data.

EDFI [22] operates by defining several faults which are triggered during the execution of the program. This is achieved by introducing a controller component process that uses a combination of dynamic and static source codes to insert a dynamic fault model.

Xception [23] presents a tool that exploits the debugging and performance monitoring features of modern COTS processors for injecting faults.

GOOFI [24] is a tool able to inject faults into the data area of programs before their execution; this tool is capable to generate single or multiple transient faults.

G-SWFIT [25] is a technique for injecting faults in code, based in different types of faults and their statistical frequency. This technique proposes a set of fault model operators that enable the injections of faults even when the source code of the target program is not available.

Commonly SWIFI techniques target applications with very high repeatability and reproducibility. Depending on the methodology implemented, intrusiveness issues can be present. Additionally, controllability and time resolution on SWIFI can be restricted to assembly level instructions with time limitations, therefore faults in the pipeline of instructions are impossible. Commonly, faults are also restricted to specific locations due to system architecture or privilege issues.

1.4 Fault injection in Operating Systems

Operating System reliability validation is quite difficult to achieve. Operating systems reliability has been studied for decades [26, 27], nonetheless, it remains one of the major areas of concern in many systems. The main reasons why operating system dependability is an issue, has mainly to do with the fact that this systems are very complex. Operating systems often have to be capable of handling many different kind of systems and architectures. Furthermore, with each technological advancement in hardware and software, constant changes need to be made on different elements of operating systems to cope with the hardware and software evolution. And finally, many operating system are commercial focused and often the companies are not interested in applying the diverse methods that have been developed to automatically test operating systems robustness in their development cycle.

One method was implemented in the Crashme program [28], where data composed of randomized values in memory were executed as code segments by a large numbers of spawned processes. Similarly, the Fuzz project [29] used random noise to data for discovering robustness issues in the operating systems.

Other commonly used approaches modify the execution of the system calls of an operating system: in FERRARI [21], the system calls made by the processes are intercepted and then modified returning faulty values; BALLISTA [30] adopts a similar approach that feeds random or erroneous inputs to the system call in order to evaluate the behaviour of the functions belonging to the POSIX-API.

In [31], faults are injected into the driver programming interface so that the effects of faults on the device drivers can be characterized. Similarly, other attempts to characterize the ability to cope with faults into the operating system functions was made in [32].

Software implemented fault injection is often focused in the application programs running in the system rather than in the operating system itself. Elements of the operating system provide services to higher applications and often these have been not considered in the main dependability studies. In recent years, techniques have been developed to target the operating system. Some studies implemented simulation tools for fault injection in operating systems [33, 34]; such studies used software such as emulators or virtual machines. In these applications, functions are used to inject faults into the virtual environment where the Operating System is running. In [33] a Virtual Machine environment that operates in QEMU (an open source machine emulator and virtualizer) is presented, injecting faults into the CPU registers, RAM data, storage system and networking I/O. In order to provide a wide scope of fault injection targets, [33] proposes to inject faults into the environment of a virtual machine; moreover, this method has a high complexity. In [34], faults are emulated by mounting a virtual machine in a custom engine capable of generating injections into elements of the machine such as memory elements, CPU registers and other hardware elements. This is achieved by using a complex compiler frame designed to support analysis of programs and operating system code. This approach is very complex and a good knowledge of the application running the virtual machine is needed.

In [35], fault injection is made into different signals from the CPU, the system calls and internal functions of the kernel. This is achieved by tracing the processes and tracking kernel calls, then the fault injection method introduces bit flips into the parameters provided to the kernel call or the underlying kernel functions. This approach is highly intrusive and requires the execution of the process to be stopped in order to trace it.

The option of making fault injections via loadable kernel modules [36] is simple and is a possible solution to the problem. Kernel modules are objects that are introduced into the kernel and are capable of exporting kernel symbols that can be functions or data structures. An implementation of such modules can be seen in [37]: this approach provides on-demand access to the application's virtual address space, as well as to the processor's context, and it injects into the applications' data segment and code segment, omitting the elements of the kernel that provide services to the applications.

1.5 Redundancy Techniques

After fault injections have determined which parts of a system are critical the following step typically is to add mechanisms to the system that enables the detection and recovery from possible faults. In order to do so, different techniques have been developed over the years, and most of these techniques can posses one or more of the following characteristics:

- Modular redundancy: different elements of the systems are multiplied and they may be used in parallel in order to determine if a fault has affected the output.
- Time redundancy: specific elements of the system are run multiple times in sequence and the output are compared to check for faulty results.
- Information redundancy: The information used by the system is multiplied and additional data (check-codes) can be added in order to detect any fault.
- Versions redundancy: Multiple versions of the system or its modules are produced so that these systems are immune to particular faults affecting the other versions.

Techniques using these principles have been implemented for a long time. For example, during the second world war some planes (e.g. Ilyushin 2 Sturmovik) had a dual landing gear system, the main system was an pneumatic system, but in the case of failure or damage, this system could be disconnected, and then a hand crank would allow the pilot to lower the landing gear using a mechanical system. This example is the implementation of Dual Modular Redundancy (DMR), and in this case, redundancy technique is using modular redundancy and version redundancy. The modular part comes from the fact that the module is being duplicated, in the sense that an additional module is installed that performs the same operation of the original, but this module is a different version because it operates in a purely mechanical and not pneumatic-mechanical principle.

1.5.1 Redundancy in Computer systems

These kind of modular redundancy techniques are still relevant, in computer systems it is quite common to find Triple Modular Redundancy techniques in modern critical

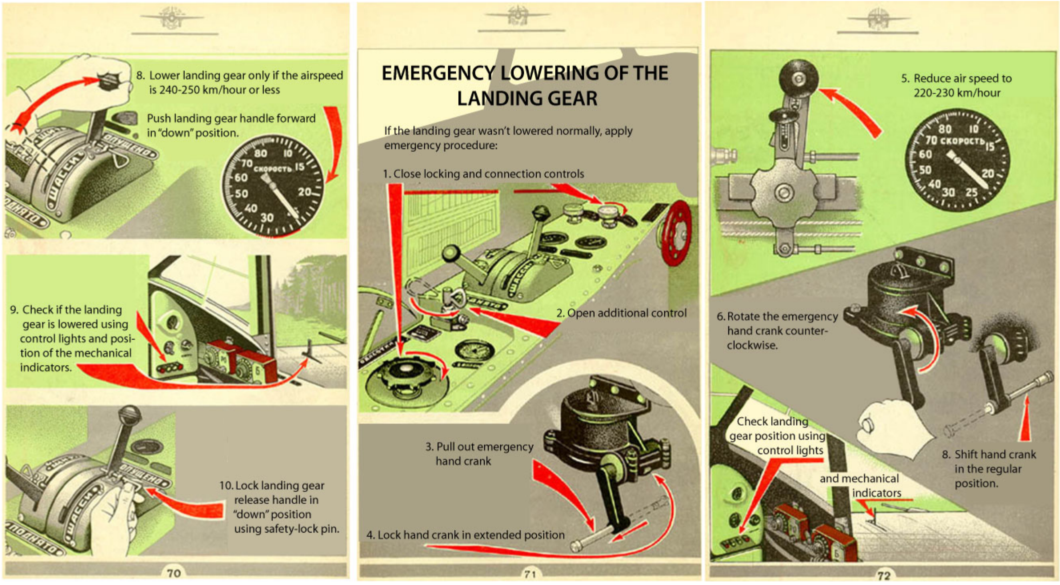

8. Lower landing gear only if the airspeed is 240-250 km/hour or less
Push landing gear handle forward in "down" position.
80
10
70
СКОРОСТЬ
15
60
50
20
40
30
ОПУЩЕНО
ШАССИ
ПОДНЯТО
9. Check if the landing gear is lowered using control lights and position of the mechanical indicators.
10. Lock landing gear release handle in "down" position using safety-lock pin.
70
EMERGENCY LOWERING OF THE LANDING GEAR
If the landing gear wasn't lowered normally, apply emergency procedure:
1. Close locking and connection controls
2. Open additional control
3. Pull out emergency hand crank
4. Lock hand crank in extended position
71
5. Reduce air speed to 220-230 km/hour
80
10
70
СКОРОСТЬ
15
60
50
20
40
30
25
6. Rotate the emergency hand crank counter-clockwise.
Check landing gear position using control lights
and mechanical indicators
8. Shift hand crank in the regular position.
72

Fig. 1.1 Images from a translation of "Flight Manual: Ilyushin 2 Sturmovik with a AM-38 Engine".

mission computer systems. These techniques are similar to DMR, but implement three modules instead of two, these modules are can identical and an additional majority voting mechanism is introduced to detect faults in output of the modules. For example, in [38] the netlist is triplicated and voters are implemented by automated tool in the FPGA layout of the Leon3 processor for satellite payload electronics.

Computer systems based in FPGAs are becoming increasingly popular in specific purpose machines, but as from the previous example we can see that these machines are not immune to faults. In [39] another implementation of TMR can be seen, but this time is in a FPGA system. This study focuses in the optimal design of TMR for FPGA based digital filters, the results demonstrate that the number and design of the voters can affect the fault tolerance of such filters.

The boundary between hardware and software redundancy mechanism mechanisms is not always clear. Furthermore, many techniques can be implemented both in hardware and in software, therefore we wont be focusing in that divide in this subsection. An example of how blurry the line between hardware and software redundancy is, can be seen in [40]. In this example, the fault detection in the memory management unit of a HaL microprocessor system for is made in hardware, but the correction of the faults is made in software by means of Error Correction codes

(ECC). Error Correction codes (ECC) are processes that add redundancy by encoding the output of an operation with additional information. These techniques encompass common techniques such as Cyclic Redundancy Check (CRC) and Hamming codes. These kind of approaches are quite common and are currently being implemented in the state of the art, as it can be seen in [41]. In this example hardening is introduced to a selected set of memory elements belonging to the kernel of particular application machines by using approaches such as Hamming and CRC codes. The elements of the kernel to harden are selected by profiling the system of these particular application machines in order to determine which elements are critical as far as dependability is considered.

Techniques such as CRC are known and well researched, but these techniques are still evolving. In [42], 48 new polygons are proposed for CRC providing good performance for CRC checks up to 2048 bits data segments.

Redundancy techniques have also been developed for technologies such as *Distributed Computing Architectures*. In [43] a dynamic voting approach is proposed, this approach adapts to changes in the environments executing the vote, this approach can be applied to distributed systems that posses multiple different resources pools.

1.5.2 Multi-Threaded/Process Techniques

If the redundancy technique is implemented in software, then there is another important characteristic defining this implementation. This characteristic describes how the technique is introduced to the system in terms of number of threads/processes.

Local-thread Multiplication is the implementation of a technique that execute multiple executions of a critical segment of code in a single thread. The results of each critical segment of code is stored and after all the executions are done, then compared. The main drawback of this technique is that the overhead in processing times is usually high, given that each segment of code is executed in sequence. Nonetheless this technique is extremely efficient in the usage of CPU Cache, and also this technique does not require any kind of synchronization mechanisms with other threads.

Software Redundant Multi-Thread is the implementation of a technique that is based in the implementation of the critical segments of code in identical threads, each in an individual core. After each thread has been completed all the results are compared, if they differ, then that implies that a fault is detected, depending in how many threads are used then it can be also corrected. In terms of time, this technique is more efficient than local thread, but requires some sort of multi-thread communications mechanism.

Process-level redundancy, this approach is based in the implementation of multiple instances of a program running and then comparing only the output. These multiple instances are not multiple threads in a single application but the application as a whole. This means the usage of multiple resources and processing time. Additionally, depending in the nature of the process being protected, this technique can have limited overhead impact and large effect in the memory imprint of the process being hardened.

1.6 Research Activity

Given the open source nature of Linux-based system, such systems have become very attractive for dependability studies, this is accentuated by the ever increasing number of systems that are supported, e.g. commercial embedded systems, Android devices, etc. Considering the proposed approaches available in literature, it would appear that there was no technique that considers analysis of the effects of faults in kernel data structures in Linux based systems.

The main research activity was divided into two phases. The first phase was focused in evaluating the effects of faults affecting specific kernel data structures, in order to assess how critical these fields are for system dependability [44–46]. A fault injection method was investigated and refined and it was based in a novel fault injection tool, called *Kernel-based fault-Injection Tool Open source* (KITO). Considering that the kernel space stores many different types of elements, the tool provides the possibility of an easy and rapid access to several different components of the operating system, such as process control blocks and kernel symbols. Additionally, the tool provides a means of customizing the target of the fault injection to any memory address containing an element belonging to the kernel space. Sets of experimental tests were executed in different kernel data structures and environments, while running a set of benchmark programs in order to stress the operating system. This document presents a detailed analysis of the effects of the faults in the Linux Kernel, demonstrating that soft errors affecting the kernel may produce critical effects and failures in user applications.

The second phase of the research was focused in adding redundancy mechanisms to the Linux kernel, fixing some of the issues that arose from the experimental results. These solutions were made considering *Local-thread multiplication information redundancy approaches*. The proposed fault injection technique and the redundancy method presented promising results, and the method was capable of injecting faults into a variety of targets of the kernel space, and redundant techniques seem to be able to detect and/or correct most of failures affecting these systems.

Additional studies could spawn from the approaches described in this thesis by considering other elements of the operating system not considered in this document.

Chapter 2

Synchronization in the Operating System

This research focuses in the implementation of fault injection methods in the data structures used by the main services provided by the Linux kernel, in particular focusing in those providing processes and resources synchronization. An introduction of the basics of the different elements considered in this research is preliminarily reported in this chapter.

2.1 Synchronization in Linux Systems

The main task of an Operating System is to manage the physical and virtual resources of the machine it is operating on [47]. These resources are then provided to different *Processes*, which are defined as instances of execution of a group of instructions executed in sequence in order to achieve a goal. Typically, computers run a multitude of processes; therefore, the need of different mechanisms allowing access to the limited different resources of the computer at a given time. One of such resources is CPU time, meaning that a CPU's core is processing the instructions that compose a process. In order to switch from one process to another one without interfering with the others' work, a synchronization mechanism needs to be implemented.

2.2 Process Synchronization and the Process Control Block

The *scheduler* is the entity that is responsible for synchronizing and switching from one process to the next one. In the case of Linux, since kernel version 2.6.23, the implemented scheduler is the Completely Fair Scheduler (CFS). The CFS is a scheduler based in a *run queue* that operates with a Red-Black Tree (a self-balancing binary data-search tree) to obtain future tasks to be executed, guaranteeing a fair time for insertion, search and deletion of a task in the tree. Additionally, the CFS operates with nanosecond accounting to determine the virtual runtime of the a process instead of working with counters. This means, that it bases its decision on the amount of time that the process has been running in the system and not on the values of counters, such as *jiffies*. This is done aiming to achieve precise multi-tasking. This is the idea of implementing hardware to run multiple tasks in parallel at the same speed: in order to follow this policy, the CFS also determines the order of the Red-Black Tree run queue by the priority and/or the virtual runtime of each process indexed in the Red-Black Tree. The schedulers often base their decision in the information present about each process in the system, and this information is often stored in kernel data structures such as the *Process Control Block* (PCB), a kernel data structure that is created for each process present in the system. The name of the PCB used by CFS is `task_struct`. The `task_struct` contains necessary information for the scheduler and some additional information for debugging and other operations, and this includes over a hundred fields of different variable types, pointers and others. Among those fields, the ones that are relevant to the studies presented in this thesis are the following:

- `PID`: each process present in the system has a unique identifier number, called *Process Identifier* (PID);
- `state`: current state of the process; e.g, *running* or *waiting* for an interrupt, if the task is being *traced*, etc;
- `thread_info->flags`: flags of the process; e.g., if the process is being terminated, allocating memory or if it was killed by a signal;
- `prio & static_prio`: the priority of the task to be selected and if this would preempt the current running task; for normal processes it ranges between 100

and 139. Only one of these fields is used, depending on the mode that the scheduler is running;

- `rt_priority`: used for real-time applications with priority ranging between 0 and 99.

Among all the different fields in the process control block, the ones considered for fault injection campaigns in this research activity were the `state`, the `flags` and the `prio` fields.

2.3 Mutex Semaphores

So far we have taken into consideration process synchronization in order to manage the amount of time that a process is being served by a CPU. Additional resources are present in most computer systems, and one mechanism to manage the access of different processes to these resources are the semaphores [47]. In this section we are going to have a look to the mutex semaphores.

The *mutex semaphores* or *mutual exclusion semaphores* are used in the synchronization of the different resources that a computer possesses. Semaphores are kernel symbols that are defined as structures that contain a binary-like semaphore to solve problems of mutual exclusion for shared resources, race conditions and/or critical code sections. This data structure is defined as follows:

```
struct mutex {
atomic_t                count;
spinlock_t              wait_lock;
struct list_head        wait_list;
...Debug options...
}
```

The variable `count` is the semaphore itself. The semaphore is *unlocked* when the `count` variable is 1. A value of 0 for the `count` variable indicates that the mutex semaphore is *locked*. Finally, when this variable is negative, the mutex semaphore is *locked* and possesses a *waiting list*. When the semaphore is locked, the field `wait_lock` indicates the current task controlling the mutex semaphore, whereas `wait_list` corresponds to the list of processes waiting for the resource.

As mentioned before, the mutex semaphores are defined as kernel symbols. A *Kernel symbol* is an easy way to share variables and functions among different elements of the kernel. These symbols are shared by using the `EXPORT_SYMBOL()` function. Exported symbols are then indexed in a list called `kallsyms` which is located in the `proc` pseudo file-system. In addition, the kernel symbols system provides functions that will allow import of data from the `proc` pseudo file-system directly to modules. One of such functions is `kallsyms_lookup_name()`, which returns the address of any symbol with the name provided to this function as input parameter. These functions will be utilized for the localization of the target mutex semaphores address during the implementation of the fault injection campaigns described in this document.

2.4 Atomic Operations

An atomic operation is an uninterruptible operation short enough to be considered instantaneous and indivisible. The Linux headers provide several atomic operations in their libraries, mainly logic and arithmetic operations. Because of the nature of the Linux headers libraries, these functions support different hardware architectures. These functions are often written in GAS (GNU assembler macro), and are independent of the computer's processor architecture. These operations are particularly effective in terms of process cycle execution.

Among these atomic operations, the work described in this thesis is based in the implementation of the `change_bit()` function. This atomic operation allows a single bit flip to be made on a particular address. This atomic operation is implemented as follows:

```
int foo=42;
change_bit(0,&foo);
change_bit(1,&foo);
```

In the previous example, the value of the variable `foo` is set initially to 42 (101010 in binary). With the first execution, the bit 0 (least significant) is changed so `foo` would become 43 (101011 in binary). Then, with the second execution the bit 1 (second least significant bit) is changed, therefore the final value for `foo` is 41 (101001 in binary).

2.5 Loadable Kernel Modules

Loadable kernel modules are relocatable object code [36], that can be dynamically loaded (inserted) and unloaded (removed) from the kernel. The drivers are the most common type of loadable kernel modules, however not all modules are drivers nor all drivers are modules, some drivers are loaded into the linux kernel files located in `/boot/`. All modules operate by means of callback function that are triggered when the modules is loaded into the kernel, via the `insmod` command, and when they are unloaded from the kernel, via the `rmmod`. The most simple module is the following:

```
#include <linux/module.h>
#include <linux/kernel.h>// Needed for printing in dmesg

int init_module(void)
{
printk(KERN_INFO "Hello world.\n");
return 0;
}

void cleanup_module(void)
{
printk(KERN_INFO "Goodbye world.\n");
}
```

In the previous example, the *Hello world* version of the module can be seen. The function that is called when the module is loaded is triggered by the `init_module()` macro. While the function that is called when the module is unloaded is triggered by the `cleanup_module()`. In the previous example the module would simply log into the *driver messages* log systems the messages "Hello world" and " Goodbye world", when the module is loaded and unloaded, respectively.

Chapter 3

Fault Injection Method

In this chapter the main mechanism utilized in the implementation of the fault injections campaign is discussed.

3.1 Fault Injection Tool

The implemented approach consisted in performing a injection of transient faults in a memory element by means of a loadable module inserted in the kernel [36]; the fault injection is performed in an atomic bit-flip manner, in any predefined Kernel space memory location at a defined time after the module's insertion. The module created for this approach has been called KITO (*Kernel-based fault-Injection Tool Open source*) and was described in [46]. This module is fully customizable by the parameters provided during the module insertion command (`insmod`). After the insertion of the module in the kernel, a *High Resolution timer* (`hrtimer`) is programmed by the KITO's module. The created timer triggers an atomic operation upon its expiration, and this atomic operation is responsible of making the fault injection by means of an atomic binary flip in the target memory element. The timer duration and the memory target address location of the fault can be fully customizable, as explained in the following sections. KITO can't inject a stuck-at fault, only generates erroneous information in memory data structures, but the data can be manipulated afterwards.

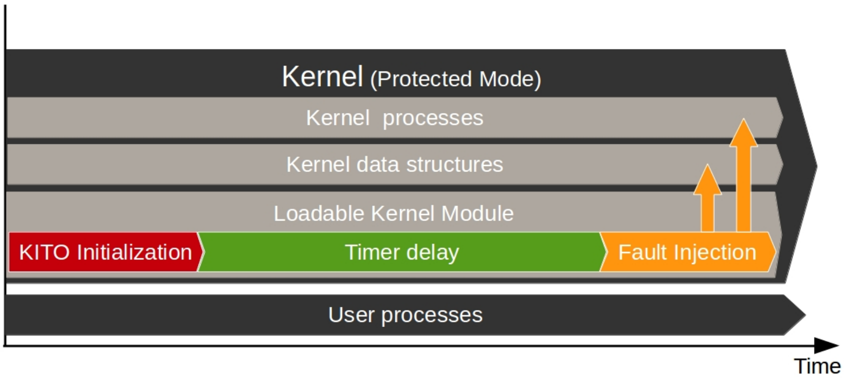


Fig. 3.1 Scheme of KITO operation.

Figure 3.1 describes the operation of KITO: at the top a large black block portraits the kernel, that contains the kernel processes, the data structures and the KITO module. The user's processes are outside the kernel block; these processes use the services of the kernel in order to execute the applications. During the insertion of the module into the kernel, it is configured in order to set up the internal variables used to define the fault injection target address and the duration of the timer delay. This set-up is represented by the *KITO Initialization* block. The *timer delay* is the time that the module will wait for a software interrupt in order to inject the fault. Finally, the fault injection block corresponds to the execution of the fault injection function which possesses a single atomic bit flip operation in order to introduce a fault in the memory elements of the kernel (kernel data structures or kernel processes).

3.2 Module's Internal Evolution

During the different stages of this research different versions of KITO were implemented. There were three major versions that were implemented during experimental campaigns, and are presented in this section.

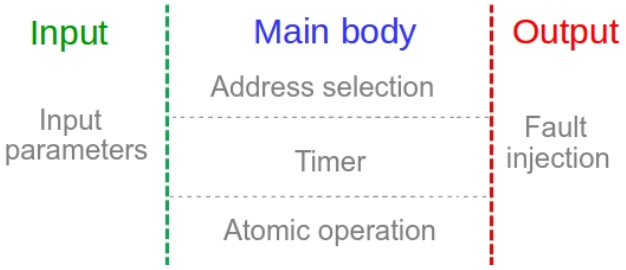


Fig. 3.2 General layout for the structure of the module versions

In general, the internal structure of the module was composed of 3 major parts; the input parameters, the main body of the module responsible for the interpretation of the input, and the output (the fault injection).

The input parameters are one of the most important elements of the KITO module, since they allow the customization of a particular fault injection. Depending in the version, KITO is capable of targeting a subset of particular memory targets, and in order to do so, the insertion of the module into the kernel has to be personalized. These parameters correspond to the inputs provided to the module at the moment of its insertion into the kernel. These input parameters determine the operational aspects of the module, such as the timer delay after which the atomic operation is called, the target of the bit flip operation and the debugging options for the module. The parameters are loaded into the module during the `insmod` command, and their dependency vary according to the adopted version. All the possible input parameters in all versions and scenarios are in accordance with Table 3.1.

- `test #n`: test number corresponding to the pointer array's index.
- `scenario`: scenarios will determine the targets location depending of which kind of target is being injected upon, this is exclusively used in V1.0
- `address`: the target custom address
- `sym`: the name of the symbol where the fault injection will be carried out; it must be an exported symbol present in `\proc\kallsyms`
- `pid`: the *process identification* number of a process; this will determine which is the address of the `task_struct` that will be considered for the fault injection target among all the different `task_struct` structures defined, one for each process present in the system

- `testbit`: it selects which bit will be modified in the target address
- `timesecs`: first component of the amount of timer delay for the fault injection (in seconds)
- `timensecs`: second component of the amount of timer delay for the fault injection (in nanoseconds)
- `debug`: enables the debugging messages in the `dmesg` system (*display messages* or *driver messages*). This is always optional, independent of the value of `scenario`.

The main body is composed of three subcomponents; the selection of the target address, the setting up of the timer and the bit flip atomic operation responsible for the fault injection. In figure 3.2 it is possible to see the layout of the different components of the KITO module, this layout is going to be used in the description of the different implemented versions. Finally, The output corresponds to the atomic operation performed by the module in a memory location.

The main difference in all versions can be found exclusively in two of the main module's components: the input parameters and the selection of the target address. All other components were identical in all versions of the KITO module.

3.2.1 KITO 0.a

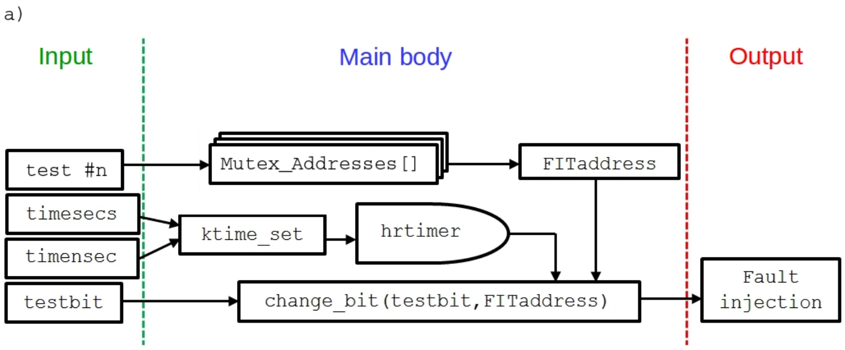


Fig. 3.3 Scheme of the KITO 0.a Module structure

In Figure 3.3 it is possible to observe the scheme of the version 0.a of the KITO module [44], the only possible target for this version of the loadable kernel module was the pre-existing mutex semaphores in the operating system. This was the first module created specifically for evaluating if this kind of fault injection was feasible, and if it was, then evaluate if the disruption of the availability of different resources would affect running applications and the operating system itself.

In details, this was the most basic version and it only had the parameters needed to set-up the timer delay after which the fault injection is made, the test of the target address to be modified and a trial number. This last one was needed in order to select the target for the fault injection from a configured array pointer (`Mutex_addresses[]`). This method is very basic and is unreliable given that the values of the pointers were preloaded at the moment of the compilation of the module and would not be able to be updated during the implementation of the module. Therefore, if an operation would have had changed the specific value of one of the pre-set targets address in the kernel memory then this target would not be able to be injected upon. Additionally each time a fault has to be made in a new target that is not in the pointer array then the module needs to be modified and recompiled.

3.2.2 KITO 0.b

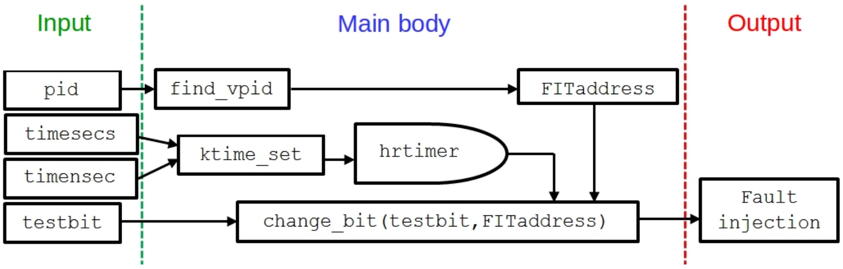


Fig. 3.4 Scheme of the KITO 0.b Module structure

In Figure 3.4 it is possible to observe the scheme of the version 0.b of the KITO module [45].

This was the first version in which the target was selected automatically, but only considering a particular type of data structure, the process control block. The main interest for fault injection campaigns in the process control block was to determine how faults would affect the operation of the Scheduler, and if there were disruptions, how these would affect the operation of the different processes running in the system providing services to the user applications.

In this version the limitations of version 0.a were overcome, because that no modification in the Linux kernel would prevent the operation of the module and no recompilation is needed when targeting new addresses in memory. Nonetheless, this is true only when considering a particular type of data structure, the *Process Control Block*. As explained in section 2.2, this structure is unique for each process that exists in the system, and contains large amounts of information of the operation of the *Scheduler*. This automatic address selection process will be explained in detail in the following version.

3.2.3 KITO 1.0

KITO version 1.0 is the most complete version of the fault injection module utilized in this research activity [46]. KITO 1.0 included the automatic address selection mechanism from version 0.b, and additional mechanisms were included. The most novel aspect of this version is that in theory is not limited to a specific fault injection target type unlike it's predecessors, the main idea was to generate a fault injection tool capable of generating faults in all memory elements of the kernel space. And in order to do so, in this version some of the input module parameters are optional and others are mandatory depending on the nature of the intended target in memory. So, in order to organize the dependencies of all the parameters, different predetermined scenarios were defined as follows:

- Custom address: A particular address can be targeted for fault injection
- Kernel symbol: The module will automatically obtain the base address of the target symbol given its symbol name
- Process descriptor: Any element of the `task_struct` of any process presented in the system, given the PID value, can be set as a target.

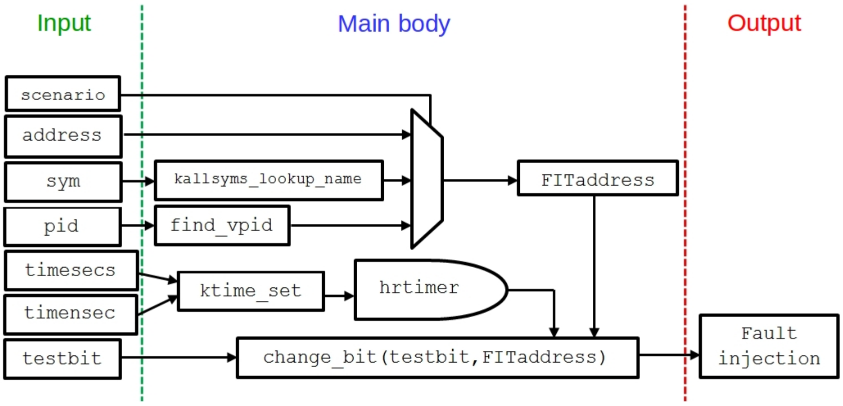


Fig. 3.5 Scheme of the KITO 1.0 Module structure

Table 3.1 Scenarios parameters requirements

Scenario	Target		Timer
	Address	bit offset	
Custom address	Address	testbit	timesecs timensecs
Kernel Symbol	Sym	testbit	timesecs timensecs
Process descriptor	PID	testbit	timesecs timensecs

In Table 3.1, the first column corresponds to the fault injection scenario in which the module is going to operate. The target is the necessary information for the selection of the target address, this column is composed of two sub-columns: the first (left) indicates which field needs to be provided to the `insmod` command in order to automatically obtain the corresponding address location. Whereas, the second sub-column (right) indicates which is the bit of the obtained address that is going to be modified. In the right, the Timer column is shared among all the scenarios, and corresponds to the amount of time that the timer is going to be waiting before making the fault injection into the kernel.

3.2.4 KITO Insertion Examples

In order to clarify how the module is inserted into the kernel here are some examples.

```
insmod KITO.ko scenario=1 sym=swapon_mutex testbit=1 timesecs=5
```

In this first example, the KITO module is inserted in the kernel using scenario 1 (Kernel symbol) and makes a fault injection in the second least significant bit (`testbit` set to 1) from the base variable of the structure defining `swapon_mutex`. The fault injection is made 5 seconds after the insertion of the module to the kernel.

```
sudo grep 'swapon_mutex' /proc/kallsyms
ffffffff96874540 d swapon_mutex
insmod KITO.ko scenario=0 address=18446744071940031808 testbit=1
 timesecs=5
```

The second example is equivalent to the first one. In this case the address of the swapon mutex is given directly as a pointer address (18446744071940031808 in decimal).

```
insmod KITO.ko scenario=2 pid=1 testbit=5 timesecs=2
timensecs=500000000 debug=1
```

In this third example, the KITO module is inserted in the kernel using scenario 2 (Process descriptor) and makes a fault injection in the 6th least significant bit (`testbit` set to 5) from a programmed field of the process descriptor of the process with a PID value of 1, commonly `init` (depending in the initialization daemon). The fault injection is made 2,5 seconds after the insertion of the module to the kernel (2 seconds plus 500000000 nanoseconds). Additionally this insertion of the module will display debug messages in the `dmesg` system.

3.3 Address selection

In order to determine where the fault is going to be injected, a pointer needs to be defined. This pointer was called `FITaddress`. The selection of the content of this pointer is done differently for each of the scenarios.

In the *Custom address* scenario, the `address` variable loaded from the parameters is copied directly into the `FITaddress` pointer. It is important to take into consideration that the custom address needs to be a logical variable. The module cannot set the target address to have a base value for the bit flip operation in the internal of a logical element. If the user wants to inject faults in the middle bit of a memory variable, then `FITaddress` must correspond to the base value for the variable in question and `testbit` is the offset to select the particular bit.

In the *kernel symbol* scenario, the address will be obtained by the `kallsyms_lookup_name` and the `sym` parameter function.

```
FITaddress = kallsyms_lookup_name(sym);
```

The symbol's name is provided in a string format in `sym`. This is provided during the insertion of the module as an input parameter. The lookup name function will automatically obtain the address of `sym` from the `kallsyms` file in the `/proc/` pseudo-file system. In order to modify a symbol of a structure nature or similar, an offset can be made directly into `FITaddress`, but it is strongly recommended to make structure pointer of the desired target and use the `container_of()` macro.

```
#define offsetof(TYPE, MEMBER) ((size_t) &((TYPE *)0)->MEMBER)
#define container_of(ptr, type, member) ({            \
 const typeof( ((type *)0)->member ) *__mptr = (ptr);    \
 (type *)( (char *)__mptr - offsetof(type,member) );})

struct some_list {
 int var_3;
};

struct some_struct {
 int var_1;
 int var_2;
 struct some_list list;
};

int main()
{
 // Original structure
 struct some_struct original_struct;
 original_struct.var_1 = 33;
 original_struct.var_2 = 114;
 original_struct.list.var_3 = 42;

 // Pointer to an element of the original structure
 struct some_list *element_pointer = &original_struct.list;

 //Return of the pointer structure
 struct some_struct *return_pointer_struct = container_of(\
  element_pointer, struct some_struct, list);

 printf("var_1 = %d\n", return_pointer_struct->var_1);
 printf("var_2 = %d\n", return_pointer_struct->var_2);
 printf("var_3 = %d\n", return_pointer_struct->list.var_3);
/* The values printed are 33, 114 adn 42, and are read from
a pointer structure. */

 return 0;
}
```

In this example of the application of the `container_of()` macro, we provide a pointer to one of the elements of an already defined structure (`*element_pointer`), and then we can obtain a pointer structure (`return_pointer_struct`) to every single element of the original structure. In order to apply this to KITO we just take one of the elements of this pointer structure as `FITaddress`.

Finally, for the *process descriptor* scenario, it is necessary to provide the PID number of the considered process. In this case, the value of the PID must be given to two functions:

- `find_vpid()`: this function will search for the identifier by its ID
- `pid_task()`: this function will obtain the address of all the fields in the `task_struct` and store it into a structure pointer; additionally, it is necessary to specify which ID type is provided to this function. The possible types are process ID, process group ID and Session ID. In the case of the KITO module, `PIDTYPE_PID` indicates that `pid_task()` must search for a process ID.

The following lines of code correspond to the implementation of both functions previously described in order to load the target of the pointers into the FITaddress variable.

```
struct task_struct *t = pid_task(find_vpid(pid),PIDTYPE_PID);
FITaddress = &((*t).state);
```

In the previous example, the first line takes every single field of the target task_struct and stores their address in a pointer structure called t. Then in the second line, the address of the state field of the process control block is going to be saved in the FITaddress. In order to select another target field from the task_struct the state in this line needs to be replaced with the desired field, and then the module recompiled. This is made in order to leave the module as clean as possible regarding the elements that are not directly involved in the fault injection process. The more logic introduced, the more complex the module becomes, and particularly complex when considering data structures such as the task_struct. Furthermore, the larger the logic sections are in the set-up phase, the more CPU time this section will take to complete.

Finally, when using the optional debugging messages in the dmesg (display message or driver message), the declaration of the format of &FITaddress in the output strings needs to be modified according to the target's data type. For example if the desired target is an integer the format must be %d in the different printk lines, but of the desired target is an float, then %f needs to be placed in these lines.

3.4 Timer Set-up

The delay after which the fault injection is made is done by means of a high resolution timer (hrtimer). This timer is defined in the Linux libraries and operates using a red/black tree self-balancing structure where the first timer to expire is at the head. After the expiration of this timer a callback function is called. This function is responsible of the fault injection. The full implementation of the hrtimer is as follows:

```
delay_in_secs = timesecs;
```

```
delay_in_ns = timensecs;
ktime = ktime_set( delay_in_secs, delay_in_ns );
hrtimer_init( &hr_timer, CLOCK_MONOTONIC, HRTIMER_MODE_REL );
hr_timer.function = &fi_hrtimer_callback;
hrtimer_start( &hr_timer, ktime, HRTIMER_MODE_REL );
```

The first three lines set the variables for the duration of the timer. Then the fourth line initializes the timer structure and the operation modes of this timer. This implementation, the clock tick is set to CLOCK_MONOTONIC which indicates that the start value of the tick counter is going to be zero, and the mode is HRTIMER_MODE_REL indicating that the time measurement is a relative time amount after the creation of the timer, and not an absolute time value of the computer's internal clock. The following line sets the pointer to the function that is called after the expiration of the timer (callback function), and in this case the function is called fi_hrtimer_callback. Finally, the last lines starts the timer.

3.5 Fault Injection

The fault injection is made in the callback function of the timer. This function is defined as follows:

```
enum hrtimer_restart fi_hrtimer_callback(struct hrtimer *timer)
{
change_bit(testbit,FITaddress);
return HRTIMER_NORESTART;
}
```

The function change_bit(testbit,FITaddress) is the fault injection itself. This is an atomic operation from asm/bitops.h. This function performs a single bit-flip in the (testbit+1)th least significant bit of the value stored in the FITaddress address. The following line returns the function, and indicates that there is no need to restart the timer.

Chapter 4

Experimental Results

In this chapter the implementation of the different experimental campaigns are going to be discussed. These experimental campaigns had a similar set-up with different variations in terms of contexts, target, and kernel versions. These differences are going to be explained in detail in each individual case, and the overall approach is presented.

4.1 Tests Environments

Different tests had different environments configurations. These configurations depended in which version of the KITO module was implemented, which kind of machine was hosting the experiments, which were the target among others. Even when a quick overlook of these tests environments can be seen in Table 4.1, each section of the individual experiments described in this chapter will introduce extensive details of the environment in order to demonstrate why these experiments are significant and novel, in particular, in the effects that faults can have in different kinds of targets.

The fields of Table 4.1 have the following definitions:

- Tests: describe the name of the tests and each test will be referred in a section in this chapter.
- KITO Ver.: KITO version implemented during the test.

Table 4.1 Tests Environments

Tests	KITO Ver.	Test Machine	Target	#FI	Kernel
Test I	V0.a	Live	Mutex	450	3.3.7
Test II	V0.b	Virtual	PCB (state)	703	3.11.0-15
Tests III	V1.0	Virtual	Mutex PCB (state) PCB (flags) PCB (prio)	9056	3.18.20

- Test Machine: kind of machine that hosted the experiments. There were two kind of machines: live machines, for tests made directly in hardware; Virtual Machines, for tests running in a virtualized environment.
- Target: What kind of data structure was injected upon in each experimental campaign. Mutex indicates fault injections made to the mutex semaphores, while PCB indicates fault injections made into a Process Control Block.
- #FI: Number of Fault injections made in each experiment.
- Kernel: Kernel Version in which fault injections were made.

4.2 Experiments Overall Set-up

The general implementation of experiments using the loadable kernel module was made automatically by a bash scripts loaded in the `rc.local` files. The `RC.local` is the first script that the user of a Linux based machine's boot can modify without the need of recompiling the kernel. This script is executed directly by the kernel, thus any script inside this file will have kernel-level privileges, and this is the feature that is exploited by the KITO module. In addition to the fault injection module insertion, a benchmark program is ran in parallel in order to stress the operating system in an operational condition. After the completion of this benchmark program, the computer will reboot and perform the following fault injection test. In order to guarantee that the experiments are performed in identical conditions, all tests were performed in machines with ram-disks. A ram-disk is a logical file-system unit that is setup using the system's RAM memory, therefore it is a volatile file-system that guarantee identical conditions with each reboot. A representation of each individual fault injection test is described in Figure 4.1, the time is represented in the horizontal axis and it is not to scale, and each individual fault injection time in a campaign is customizable down to nanoseconds by means of hr-timer.

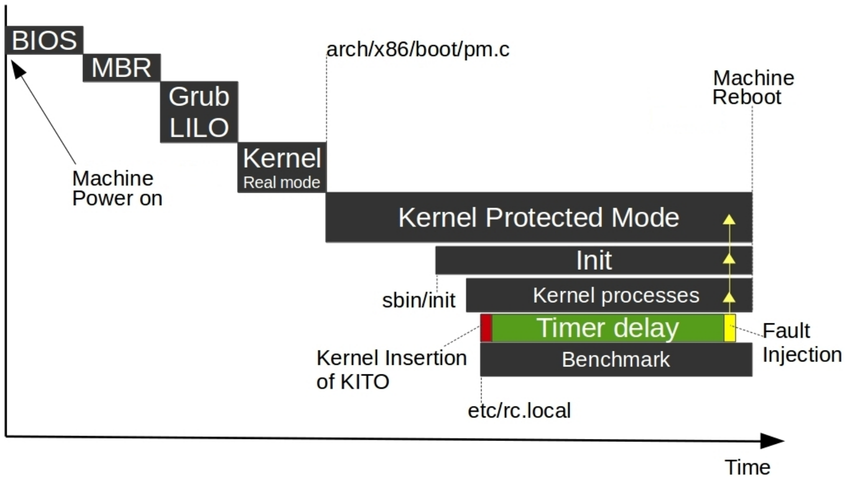


Fig. 4.1 General representation of each individual test carried out in the virtual machine.

The different blocks in Figure 4.1 are the following:

- BIOS: the check of the devices in the machine.
- Master Boot Record (MBR) check: the check of the first record in the file system that describes the distribution of different partitions and boot options of the systems installed on them.
- GRUB/LILO: the element that manages the options given by the MBR and takes a decision in the boot or presents the options to the user.
- Kernel: loads the kernel fetch code into the system memory and takes over the management of the machine resources.
- `init`: the first process created in the system; all processes will be created by the execution of system calls from `init` or its childrens.
- Kernel processes: all the processes initialized by the kernel that are responsible for providing services to higher level applications.
- KITO: the insertion of the module that manages the fault injection. The module is inserted into the system by the `rc.local` script, without making a modification in the kernel, with a less intrusive approach.

- Benchmark Programs: just after the KITO module insertion into the kernel, a benchmark is executed by means of the `rc.local` script. After the conclusion of the benchmark program a reboot is executed.

4.3 Fault Effects Classification

In all experimental campaigns there were observable noxious effects to the operating system. These effects took place after the fault injection and modify the way that the operating system behaved. In order to classify these fault effects we took the characteristics of the abnormal behaviour presented by the operating system and classified the effects accordingly. The full list of effects is the following:

- POF (Power Off Failure): After the benchmark program completed its operation the operating system remained idle and did not begin the power-off procedure (or reboot).
- SHPO (System Hanged in Power Off): The system stops while executing the power off during system reboot. This means that the benchmark program was executed and its operation completed.
- SDPO (System Delayed Power Off): The system took longer than usual to power-off during the reboot, up to twelve minutes.
- BUI (Broken User Interface): The User Interface (UI) of the system broke generating digital artifacts and bugged windows, but the operation of the system carried on.
- BS (Black Screen): the system hanged during the execution of the benchmark and the machine was unresponsive with a black-screen. Consequentially, the benchmark program operation did not complete.

4.4 Implemented Benchmarks

During the different experimental campaigns a variety of benchmarks were implemented to stress the machine in which the fault injection was performed. These benchmarks were the following:

- IOzone3 [48]: a tool that generates and simulates Input-Output operations. Additionally, IOzone3 provides metrics on the amounts of operations performed. In particular, the operations are performed as writing and reading operations in the File-system.
- Netperf [48]: a client-server tool to evaluate the network performance, particularly in TCP/IP. This tool provides metrics on the data transfer rate and processing rate of the connection between the server and the client.
- Matrix product (MP): A 1500x1500 matrix multiplication program is used to simulate CPU intensive operations.
- SCP: a client-server application used to evaluate the I/O operations in conjunction with network communications.
- GZIP: the compression of a file generates heavy load in the CPU and also on I/O operations in the file system, thus combining CPU and I/O-bound applications.

In all the applications of these benchmarks the output was taken into consideration. When possible the tests output was compared to the output from a *golden experiment* version of the test, meaning comparing the metrics and the binary difference of the output files.

4.5 Tests I: First Mutex Semaphores Experiments

The basic elements of the fault injection method were tested in this study. The injection in memory implementing a fault with a timer and an atomic operation were conducted with success up to a certain degree. In this early version of the KITO module, all the parameters for the fault injection were in the code of the loadable kernel module, giving no degree of customization of the target address. All addresses were loaded into an array with the pointer address to the mutex semaphores extracted from the `proc` pseudo file system manually. This experimental campaign based in this method was presented in [44], and were made into a live machine using Linux kernel version 3.3.7. Additionally the delays were programmed into two different pre-set times. Two different benchmarks were implemented in the tests, Gzip and SCP.

4.5.1 Results

During this experimental campaign the classification system was not established yet, but a total of 4.44% of the test presented some kind of abnormal behaviour. The effects of faults in the mutex semaphores was revisited in the experiments of section 4.7.

4.6 Test II: First Process Control Block Experiments

The general set up of the experiments were following the guidelines described in section 4.2. There were significant differences in this experimental campaign, the main being the target of the fault injection campaign. In this campaign the faults were injected into the `state` field of the process control block. This experimental campaign was also the first time when the target was automatically selected using the functions provided by the Linux headers libraries. Finally, this fault injection campaign took place in virtual machines instead of live machines, probing that a simulation based environment is viable with this method. Both the virtual machines and the host machines were running with Linux kernel version 3.11.0-15, and the virtual machines environment was made with Virtual Box 4.1.12.

Given that the test were performed in virtual machines, there was the need for a mechanism to pass the experimental results from the virtual machine to the host machine. For this, a shared folder file system was implemented between the host and virtual machines. All of the files managing the different process descriptions for the automated decision of the target were placed in this file system. In order to manage these two layers (host machine and virtual machine) and the files in the shared file system, an additional layer of scripts was introduced that would manage the creation and destruction of virtual machines and would store the results in the output folder, a graphic representation of this two layer model can be seen in figure 4.2.

The virtual machine layer has a script that follows the set-up described in Section 4.2. This script takes name of every single process in the system at the moment of the test (anything before the `RC.local` execution), then picks the first process that has not been selected before in a previous test, and then proceeds to insert the module to make a fault injection to the `state` field of the `task_struct` of the selected

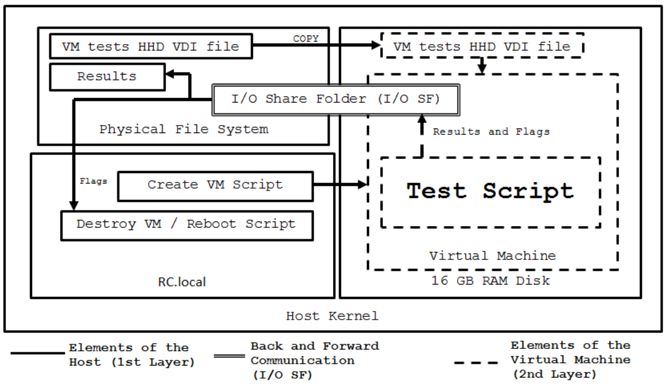


Fig. 4.2 Representation of the two layers model.

process (figure 4.3 show the schemes of the script described). Finally, the benchmark program used in these experimental campaign was Gzip.

The target for the fault injection was the `state` field of the process control block, and the main idea was to change the first bit in such way that a fault would change the current state of the process to another, or even to an invalid state. The different considered states where the following:

- `TASK_RUNNING`: Task is running, the value of the state field is 0.
- `TASK_INTERRUPTIBLE`: Task is waiting for some condition to exist, and it could become runnable if a signal is received. The value of the state field is 1.
- `TASK_UNINTERRUPTIBLE`: Task is waiting for some condition to exist, but the task will not become runnable if a signal is received. The value of the state field is 2.
- `TASK_ZOMBIE`: Task is terminated but the descriptor is kept in the case that the parent task needs to access the task descriptor information. The value of the state field is 4.
- `TASK_STOPPED`: Task is stopped due to a signal or is being debugged. The value of the state field is 8

4.6.1 Results

The different faults effects were distributed according to the following table:

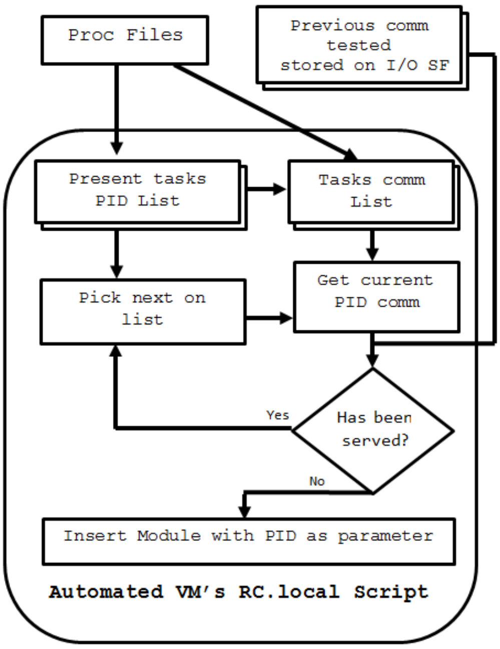


Fig. 4.3 Virtual Machine's script flowchart

Table 4.2 Distribution of the results

Final State	#FI	POF	SHPO	SDPO	BUI
TASK_RUNNING	166	2	16	22	2
TASK_INTERRUPTIBLE	10	0	0	0	0
TASK_UNINTERRUPTIBLE	165	2	4	8	0
TASK_ZOMBIE	165	0	0	0	0
TASK_STOPPED	167	2	8	0	2

In table 4.2, the column "Final State" indicates what was the final state achieved after the injection of faults in each experimental run, in most of the cases the preceding state was TASK_INTERRUPTIBLE. #FI corresponds to the number of fault injections (one for each process in the system up to the point of insertion of the module), and the following columns follow the classification described in section 4.3. Overall most of the experiments started from TASK_INTERRUPTIBLE, while the rest started from TASK_RUNNING.

Over 25.3% of the experiments in TASK_RUNNING presented failures, becoming the most detrimental state to change into. All the processes that presented failures going into TASK_INTERRUPTIBLE and TASK_STOPPED also presented the same failures going into `TASK_RUNNING`. But from all the considered processes only `Init` and `RC` presented failures going into `TASK_RUNNING`, `TASK_INTERRUPTIBLE` and `TASK_STOPPED`. Apart from these processes, not a single process that presented an abnormal behaviour was shared between `TASK_INTERRUPTIBLE` and `TASK_STOPPED`.

Additional experiments were made also to test an invalid state, i.e., putting the state to a value not recognized as a valid one. A total of 166 experiments were carried out for each bit and in all the cases no detrimental consequence on the system was detected.

4.7 Test III: Extensive Experiments

In this subsection the experiments are made in the final version of the KITO fault injection module. All the experiments carried out to determine the effectiveness of KITO. These tests were made in elements belonging to the process synchronization and resource locking aspects of the Kernel. The experimental set-up was made in an identical Virtual machine environment to the one used in section 4.6, but this time the virtual machines were running in Virtual-Box 4.1.12 and all Linux kernel versions were 3.18.20. As like in section 4.6, all experiments were loaded into the `RC.local` of the virtual machines scripts to run the benchmark program.

Experiments were performed to evaluate the capabilities of the KITO module. These experiments consist of fault injections into different elements of the kernel's process synchronization while running a benchmark program. A greater number of benchmarks have been adopted, and these benchmarks were selected due to the different nature of the stress that they place on the operating system. The adopted benchmark programs are IOzone3, Netperf, Matrix product, and Gzip.

The hard-disks of the virtual machines running these experiments were loaded into a ram-disk in order to avoid fragmentation issues and to ensure that every test is being run from the same starting point. Additionally, following the same guidelines used in section 4.6, all the information about the results was stored in the file system of the hosting machine via shared-folders.

The fault injection campaigns considered two main targets:

- The semaphores: Faults are injected into `count` variable inside the mutex semaphore data structure.
- The Process Control Block: Faults are injected into three different sample fields of the `task_struct` (`state`, `flags` and `prio`).

The `rc.local` scripts will execute the tests using kernel level privileges. In each test the bits considered are analyzed by 2 individual injections at random times.

4.7.1 Mutual Exclusion Semaphores Experiments Subset

Faults were injected into the *mutex* semaphore structure's `count` variable. As explained in chapter 2, the expected values of the count variable are 1 when the semaphore is free, 0 when it is locked and a negative value when the semaphore is locked with a waiting list, which is a FIFO queue. The bits targeted were the most significant one (bit 31), the second least significant (bit 1) and the least significant (bit 0). For this experiment, a list of all the existing mutex semaphores in the system was extracted from the `/proc/` pseudo-files, and a total of 161 mutexes listed in `/proc/kallsyms` were covered. These mutexes were feed to the module via the insert parameters (`scenario`, `sym`, `pid` and `testbit`).

4.7.2 Process Control Block experiments Subset

Since the main goal is to evaluate the reliability of the kernel elements providing services to user applications, all the tasks that exist up to the point of execution of the `rc.local` script were considered, given that most of these are processes belonging to the kernel.

As explained in chapter 3, the KITO module receives a PID number and automatically obtains the address pointer to the `task_struct` associated with such PID number. The first process loaded in the Linux kernel is always `init` (with the assigned value 1); after `init`, several different tasks will be created with a specific PID value. Up to a certain point in the boot, PIDs tend to be identical from reboot to reboot, with low PID numbers, but afterwards, the PID values are differently assigned to tasks almost in a random way.

Three fields of the `task_struct` have been considered:

- state
- flags
- prio.

Table 4.3 Values of the state field of the task_struct.

Possible state	Variable value
TASK_RUNNING	0
TASK_INTERRUPTIBLE	1
TASK_UNINTERRUPTIBLE	2
__TASK_STOPPED	4
__TASK_TRACED	8
EXIT_DEAD	16
EXIT_ZOMBIE	32
EXIT_TRACE	96
TASK_DEAD	64
TASK_WAKEKILL	128
TASK_WAKING	256
TASK_PARKED	512
TASK_STATE_MAX	1024

The defined state values present in the Linux version 3.18.20 are described in table 4.3. Given the results of [45] the most common state is TASK_INTERRUPTIBLE. Therefore, in accordance with table 4.3, the value 0 is the only possible value achievable after a single fault injection for most states; this value corresponds to the state TASK_RUNNING. All the other states would require to have as a starting value TASK_RUNNING, or in the case of EXIT_TRACE, it is necessary to start from EXIT_ZOMBIE and EXIT_DEAD, or vice versa. This last scenario is highly unlikely, therefore it was not considered for tests. In most other cases the value would carry to a value not valid and not defined in the table. Additionally from [45] a single fault injection would most likely provide a faulty behaviour by changing the state to a valid state, therefore in this case to TASK_RUNNING. As a result, the tests were conducted with particular attention to bit 0. Additionally other bits were tested to determine the effects of non valid states, these bits were bit 1 and bit 2.

The flags field is an integer containing the flags of the processes, and it is defined in a bit map. The fault injection experiments focus on the effects of faults in the process flag PF_EXITING (0x00000004). With this value, the process would be flagged for termination, and it will be held in a wait state before releasing the memory and the resources assigned to it. Thus, by modifying this flag we are expecting to stop a process that would affect others in a cascading effect. Additionally, both bit 1 and 0 (0x00000002 and 0x00000001) are taken as references to determine the effects of non defined flags bits. The full list of flags is presented in Table 4.4.

Table 4.4 Valid codes of the flags field of the task_struct.

Flag	Variable value	Meaning
PF_EXITING	0x00000004	Getting shut down
PF_EXITPIDONE	0x00000008	PI exit done on shut down
PF_VCPU	0x00000010	A virtual CPU
PF_WQ_WORKER	0x00000020	A workqueue worker
PF_FORKNOEXEC	0x00000040	Forked but didn't exec
PF_MCE_PROCESS	0x00000080	Process policy on mce errors
PF_SUPERPRIV	0x00000100	Used super-user privileges
PF_DUMPCORE	0x00000200	Dumped core
PF_SIGNALED	0x00000400	Killed by a signal
PF_MEMALLOC	0x00000800	Allocating memory
PF_NPROC_EXCEEDED	0x00001000	RLIMIT_NPROC was exceeded
PF_USED_MATH	0x00002000	FPU must be initialized before
PF_USED_ASYNC	0x00004000	Used async_schedule*()
PF_NOFREEZE	0x00008000	Should not be frozen
PF_FROZEN	0x00010000	Frozen for system suspend
PF_FSTRANS	0x00020000	In a filesystem transaction
PF_KSWAPD	0x00040000	A kswapd
PF_MEMALLOC_NOIO	0x00080000	Allocating memory without IO
PF_LESS_THROTTLE	0x00100000	Throttle less
PF_KTHREAD	0x00200000	A kernel thread
PF_RANDOMIZE	0x00400000	Randomize virtual address space
PF_SWAPWRITE	0x00800000	Allowed to write to swap
PF_SPREAD_PAGE	0x01000000	Spread page cache over cpuset
PF_SPREAD_SLAB	0x02000000	Spread some slab caches over cpuset
PF_NO_SETAFFINITY	0x04000000	Not allowed use with cpus_allowed
PF_MCE_EARLY	0x08000000	Early kill for mce process policy
PF_MEMPOLICY	0x10000000	Non-default NUMA mempolicy
PF_MUTEX_TESTER	0x20000000	Belongs to the rt mutex tester
PF_FREEZER_SKIP	0x40000000	Should not count it as freezable
PF_SUSPEND_TASK	0x80000000	Called freeze_processes

Table 4.5 Distribution of the results for the fault injections in the Mutex semaphores.

IOZONE3

Bit #	#FI	POF	SHPO	SDPO	BUI	BS
Bit 0	322	4	40	0	2	2
Bit 1	322	0	0	0	0	0
Bit 31	322	2	37	0	0	0

NETPERF

Bit #	#FI	POF	SHPO	SDPO	BUI	BS
Bit 0	322	4	36	0	2	2
Bit 1	322	0	0	0	0	0
Bit 31	322	2	30	0	0	0

MP

Bit #	#FI	POF	SHPO	SDPO	BUI	BS
Bit 0	322	4	40	0	2	2
Bit 1	322	0	0	0	0	0
Bit 31	322	2	36	0	0	0

GZIP

Bit #	#FI	POF	SHPO	SDPO	BUI	BS
Bit 0	322	4	41	0	2	2
Bit 1	322	0	0	0	0	0
Bit 31	322	2	38	0	0	0

In the case of `prio`, the priority value may be changed. As explained in chapter 2, the priority range are split between 0 and 99 for real time processes and from 100 upwards is for normal processes. So, a bit flip in the 7th least significant bit changes the priority mode from real time to normal (and vice versa). Moreover, other experiments targeted the two least significant bits changing only the value of the priority and not the priority type (dynamic priority and real time priority).

4.7.3 Results Analysis

The effects of the faults were classified in accordance to the definition of effects described in section 4.3. Failures that have observable behaviour were distributed in tables 4.5, 4.6 and 4.7.

Table 4.6 Distribution of the results for the `state` field of the `task_struct`.

IOZONE3

Bit	#FI	POF	SHPO	SDPO	BUI	BS
Bit 0	166	2	23	18	2	0
Bit 1	166	0	0	0	0	0
Bit 2	167	0	0	0	0	0

NETPERF

Bit	#FI	POF	SHPO	SDPO	BUI	BS
Bit 0	168	2	24	19	2	0
Bit 1	167	0	0	0	0	0
Bit 2	169	0	0	0	0	0

MP

Bit	#FI	POF	SHPO	SDPO	BUI	BS
Bit 0	169	2	19	19	2	0
Bit 1	169	0	1	0	0	0
Bit 2	169	0	0	0	0	0

GZIP

Bit	#FI	POF	SHPO	SDPO	BUI	BS
Bit 0	169	2	21	18	2	0
Bit 1	168	0	0	0	0	0
Bit 2	168	0	0	0	0	0

Table 4.7 Distribution of the results for the `flags` field of the `task_struct`.

IOZONE3

Bit	#FI	POF	SHPO	SDPO	BUI	BS
Bit 0	165	0	0	0	0	0
Bit 1	166	0	0	0	0	0
Bit 2	164	2	13	21	0	0

NETPERF

Bit	#FI	POF	SHPO	SDPO	BUI	BS
Bit 0	170	0	0	0	0	0
Bit 1	168	0	0	0	0	0
Bit 2	168	2	12	19	0	0

MP

Bit	#FI	POF	SHPO	SDPO	BUI	BS
Bit 0	167	0	0	0	0	0
Bit 1	168	0	0	0	0	0
Bit 2	167	2	12	20	0	0

GZIP

Bit	#FI	POF	SHPO	SDPO	BUI	BS
Bit 0	166	0	0	0	0	0
Bit 1	168	0	0	0	0	0
Bit 2	167	2	11	21	0	0

In all the tables, the term #FI corresponds to the number of fault injections carried out. Table 4.5 shows the experiments in the mutex semaphores. The noxious effects are almost equally distributed independently of the kind of load given to the system; 11.56% of the injected faults in the mutex semaphores hanged the system during the power off (considering only the most and least significant bits), the most common error message for this failure on the power off screen was the time out of a process. Additional analysis of the error messages suggests that these kinds of errors messages are common when tasks are held in endless loop scenarios. These faults inhibit the mutex function to allow programs to continue to a critical section of code, limiting the ability of this process to complete its task and to exit, resulting in a deadlock scenario. Additionally, the computer is hanged during the reboot by processes other than the benchmark. In relation to faults injected into bit 1 no noxious effects were observed. Whereas, the faults made into the most significant bit (bit 31) presented effects comparable to the least significant bit.

Table 4.6 displays the results of the experiments that made faults into the `state` field of the `task_struct`. Once again, changes to the least significant bit showed to be the most critical. Given that the least significant bit changes into a valid state, therefore, providing a valid option for the scheduler to process corrupt information in the `state` field without triggering any kind of recovery mechanism. 26.34% of faults in the bit 0 resulted in a failure. A single fault injected made into the bit 1, while the state of this task was `TASK_RUNNING`, so the fault injection resulted in a value signalling to the scheduler `TASK_UNINTERRUPTIBLE` state, also providing a corrupted value.

Table 4.7 shows the distribution of the effects in the experiments involving fault injections into the `flags` field. In this case, bit indicating the `PF_EXITING` flag was the only critical one. This bit incurred in noxious effects in 20.57% of faults injected. The other two bits corresponding to undefined values did not present any effects.

4.7.4 Effects on Performance

IOzone3 and Netperf benchmarks provide exact metrics in performance, and these registered significant degradation.

IOzone3

The *IOzone3* benchmark was executed with options that would register performance in writing, reading, rewriting, writing backwards and writing in random order operations. Figure 4.4 shows two particular scenarios in which the performance was affected because of the faults. In both graphs, the performance is measured in I/O operations per second in the vertical axis. While the horizontal axis denotes each individual test performed in order. In the case of the top graph, the lower the number is, then the closer the process being injected upon is to the core of the kernel. Given that `init` has the value 1, each following process goes to higher and higher layers of the operating system. This graph shows the effects of the faults injected into the Bit 0 in the `flags` field of the `task_struct`. Finally, the red horizontal line corresponds to the mean of 20 *golden experiments* (i.e., the execution without fault injection). From this graph we can infer that a fault affecting a core process of the operating system would have higher performance degradation than a fault affecting processes closer to the user space. This was true to all the faults in the `state` and `flag` fields.

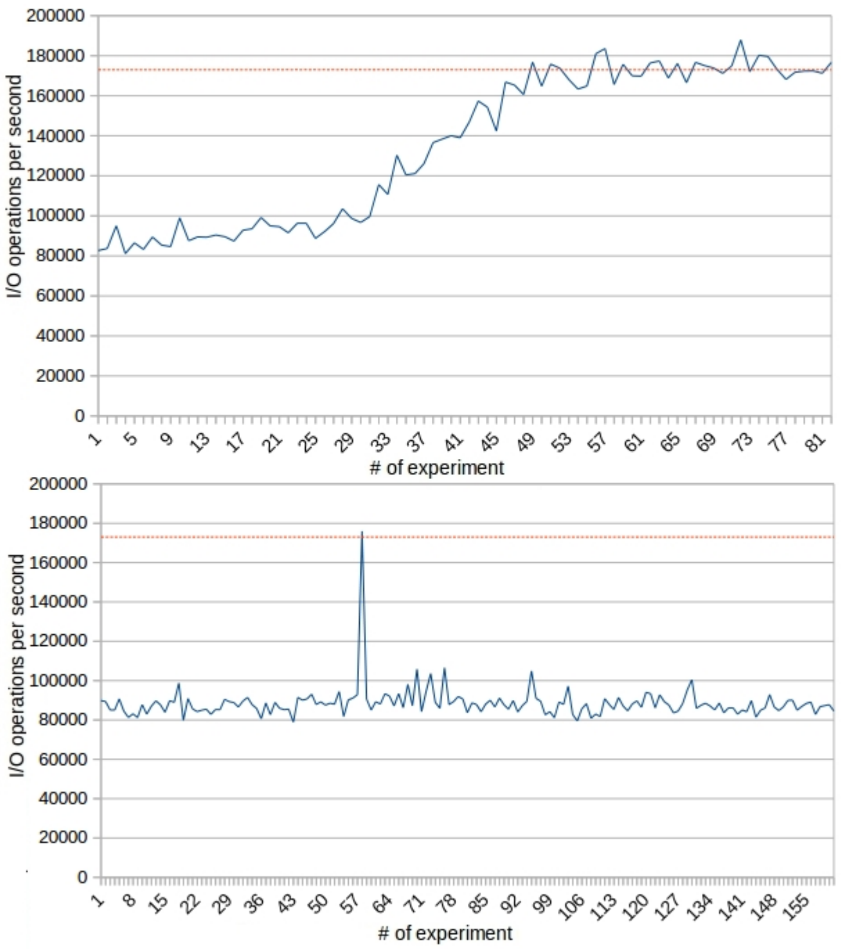


Fig. 4.4 Performance of different experiments performed with IOzone3 Benchmark. The top graph corresponds to faults affecting bit 0 in the `flags` field of `task_truct`. The bottom graph corresponds to faults affecting bit 0 in the Mutex semaphores.

Considering the second graph in Figure 4.4, the horizontal axis represents each individual mutex semaphore in order as extracted from the `proc` file system. In this case almost all the fault injections in the mutex semaphores presented a performance degradation. The average of the degradation was around 48.8% (about 88,000 operations per second compared to 173,000 for the golden experiment); only the `swapon_mutex` (number 58 in the graph) presented no degradation in its performance, but this is most likely because no swap operation was performed by the system during the test. Note that for the bottom graph there is no correlation between the number of the experiment and PID, since each experiment corresponds to a specific Mutex. So, we can state that in relation to the I/O bounded processes, faults in the mutex semaphores result in a significant performance degradation.

Netperf

The *Netperf* benchmark needs to establish a TCP link between the server and client machines and just like IOzone3 it provides the metrics of performance. Figure 4.5 describes the performance of the benchmark in its vertical axis, and this measurement is made in TCP transactions per second. The horizontal axis is defined as in figure 4.4. During the Netperf experiments, some fault injections prevented the creation of the client-server link, therefore, only the tests that managed to successfully establish the connection and execute the benchmark are displayed in Figure 4.5.

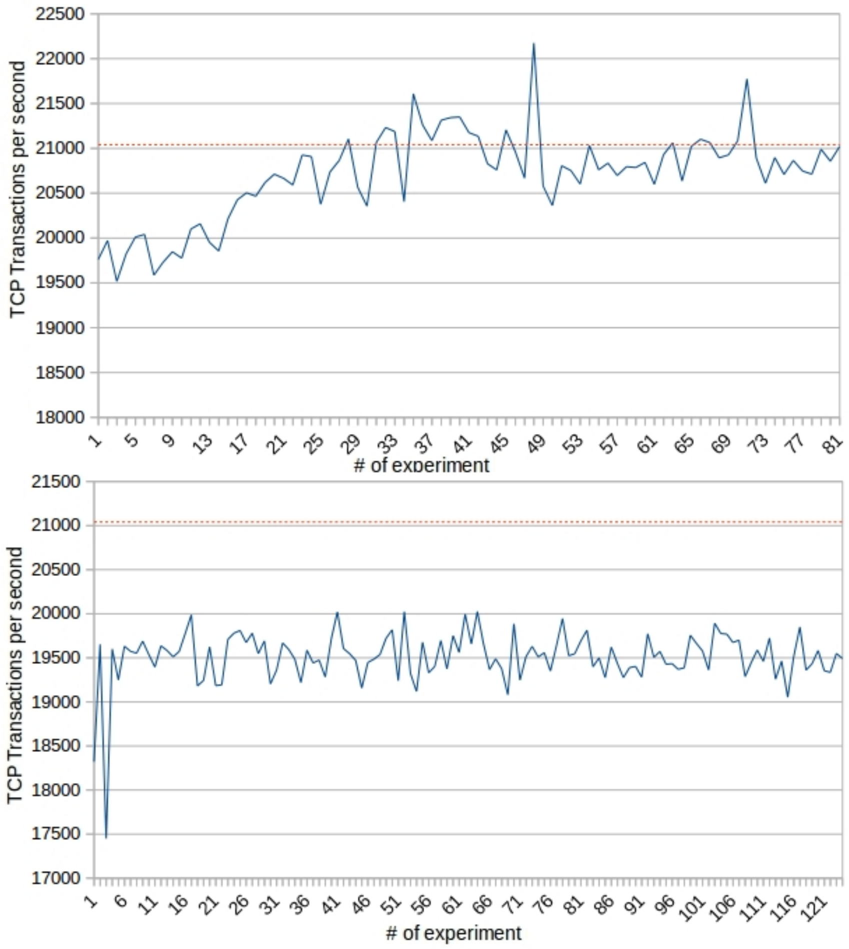


Fig. 4.5 Performance of different tests performed with Netperf Benchmark. The top graph corresponds to the writing tests on bit 0 in the `state` element of `task_truct`. The bottom graph corresponds to the tests on bit 0 in the Mutex semaphores.

Table 4.8 Connection issues in Netperf experiments

Test	#FI	Connection Failures	Percentage
state	504	12	2.38%
flags	506	11	2.18%
prio	502	16	3.18%
Mutex	966	128	13.25%

Taking in consideration the overall performance, once again in the `task_struct` experiments there is a significant performance loss in the lower PID numbers, and then incrementing to normal performance levels in processes closer to the user-space level. Again, the horizontal line (at value 21000) corresponds to the average value of 20 *golden experiments*. Finally, on the subject of faults in the mutex semaphores, the overall performance loss was almost uniformly distributed with a degradation of 7.6%

The occurrences of faults that prevented the benchmark to establish the client-server connection are described in Table 4.8. This failure was present with a higher failure rate in experiments that made faults in the *mutex* semaphores, with a 13.25% of the fault injection manifesting these failures.

Chapter 5

Redundant Techniques for Kernel Data Structures

The concluding activity of the research was concentrated on adding redundancy to the Linux kernel. These efforts were made into hardening the mutex system and the scheduler. In both cases *information-software* redundancy techniques were used. The first solution proposed was to introduce a TMR-like approach to the mutex semaphore, this would involve the triplication of the semaphore information and a voter mechanism to detect and correct all faults. The second was an *Error Detection And Correction* (EDAC) method taking advantage of the `state` field definition in the `task_struct`. Both proposed approaches have to be implemented with *local-thread duplication* because we desire to provide a broad and general solution, and not exclude the machines that are not capable of multi-threading, and because the scheduler and the mutex are in constant use it is impossible to perform a *Process-level redundancy*.

5.1 The Mutex Mechanism

The implementation of hardening techniques to the mutex semaphores system needed the modifications of a handful of files, and among them `mutex.h` and `mutex.c`. In `mutex.h` the mutex data structure is defined, alongside a couple of functions that manage some aspects of mutex, such as `__MUTEX_INITIALIZER` and `mutex_is_locked`. In addition, all the functions implemented in the mutex system have their functions

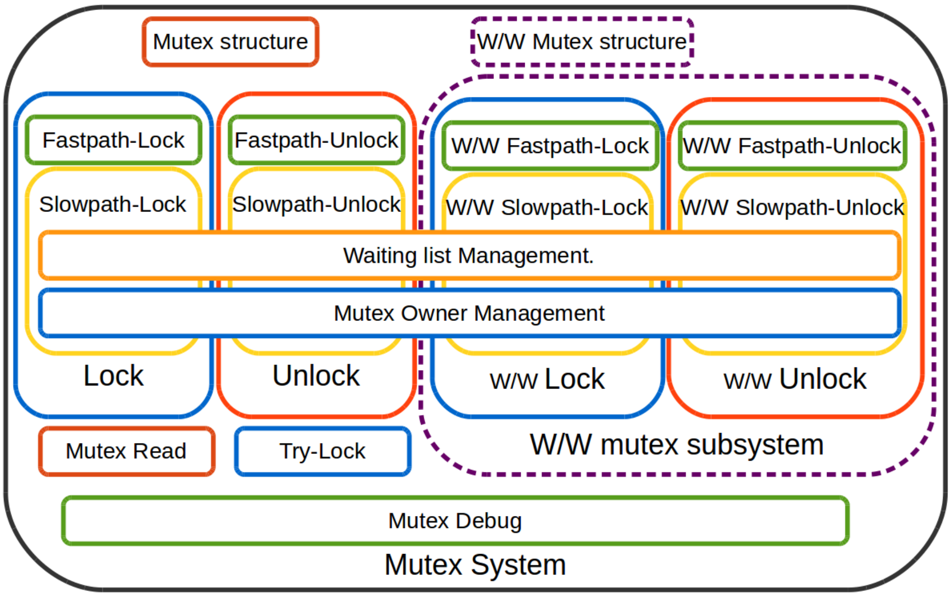


Fig. 5.1 Simplified diagram of the subsystems of the mutex system and their components.

prototypes defined in `mutex.h`. While in `mutex.c`, over 30 functions are defined which interact with the mutex semaphores. These functions can be divided into different subsets depending on the kind of operations these functions perform. The first set is the division between the lock and unlock functions: these functions can further be sub-divided into fast-path and slow-path lock/unlock functions. Additionally, there is a subset of functions intended to manage the waiting lists while performing the mutex lock and unlock operations. The `mutex.c` file also includes functions that are meant to update fields in the context of the process control block whenever a process gains or relinquishes control of a resource in the machine. Other functions evaluate the availability of these resources. Finally, there are functions used in the Wait/Wound mutex system, designed to solve the situation in which more than one mutex is called by a process in order to avoid deadlock scenarios. A simplified graphical representation of the different elements involved in the mutex system is shown in Fig. 5.1.

5.1.1 Fastpath and Slowpath Mutex Operations

The mutex semaphores have three possible distinct states; unlocked, locked and with waiting list. The current state that the mutex holds will determine which kind of operation will be performed in order to lock or unlock the mutex. There are two different approaches implemented for this. *Fastpath mutex lock* or *unlock* and *slowpath mutex lock* or *unlock*. Mutex fastpath is executed when a transition from (or to) an unlock mutex status is made. Fastpath is has a smaller footprint than slowpath because it doesn't have to manage waiting the waiting for a mutex nor the managment of the waiting list. The fastpath functions are an assembly macro to increase or decrease the `count` variable of the mutex. The fastpath function is dependant on the machine's architecture. An example of a fastpath operation is the following one:

```
__mutex_fastpath_lock(count, fail_fn)
```

In this example, `count` is the semaphore variable of the mutex structure. When the value of `count` is 1, then the function changes it to 0. In any other case (0 or negative values) the function `fail_fn` is called. `fail_fn` is always the slowpath version of the lock operation,. This occurs in any scenario when the transition is into a "mutex with a waiting list". All the fastpath functions are defined in assembly language and are architecture dependent. While the slowpath operations are primarily defined in C language with calls to the operating system's generic atomic operations. A process performing a lock/unlock operation will always try to perform a fastpath operation and if the operation fails (meaning that the mutex is not free) then it will perform a slowpath operation, the main difference of both operations is that slowpath operation takes into consideration many more variables into consideration and posses many more states when considering it as a state machine cycle. For instance only in a slowpath operation there is any interaction with the waiting list for the mutex in a lock operation.

5.2 Hardening Implementation

In order to improve the dependability of the mutex data structures, a Triple-Modular-Redundancy (TMR) technique has been adopted and introduced into the source files of the Linux kernel [49]. This approach modifies the definition of the mutex structure in `mutex.h` by adding two new count variables (named `count1` and `count2`). The role of these variables is to triplicate the information describing the current state of the mutex semaphore. Every time that the mutex is acted upon, e.g., for lock,

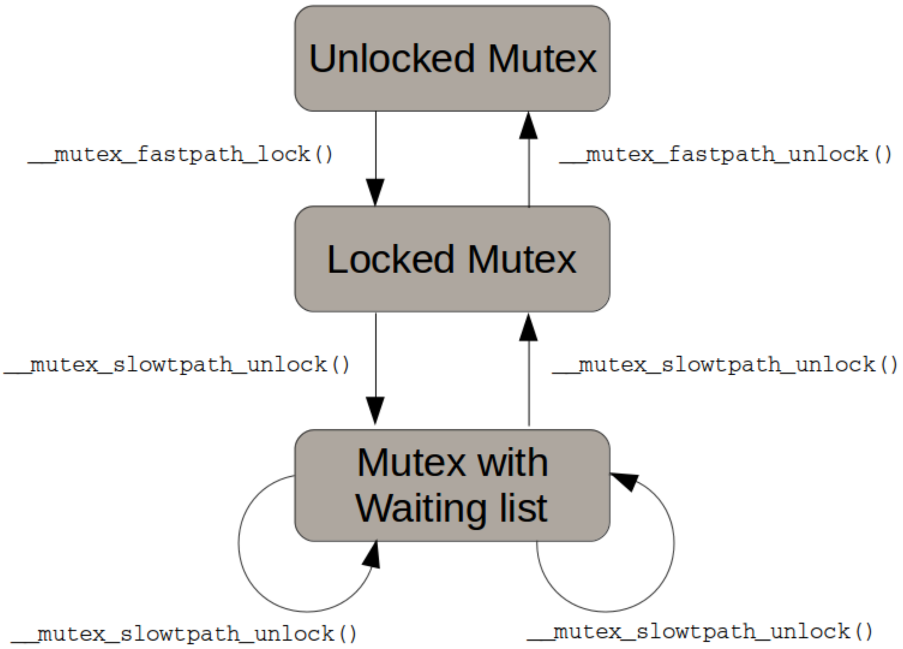

Unlocked Mutex
__mutex_fastpath_lock()
__mutex_fastpath_unlock()
Locked Mutex
__mutex_slowtpath_unlock()
__mutex_slowtpath_unlock()
Mutex with Waiting list
__mutex_slowtpath_unlock()
__mutex_slowtpath_unlock()

Fig. 5.2 Implementation of fastpath and slowpath scenarios.

unlock, trying the lock, debugging, etc., a bitwise voting function is made to check the majority of the values and then update the results of these operations in all three `count` variables belonging to the mutex data structure. Additionally, each time that the mutex is about to be used, meaning right before any read or write operation, a majority vote operation is also made in order to detect and correct any fault that have occurred in the count variables since the last operation executed with the mutex. In like manner, after any write operation every single variable have to be updated to its new values. This ensures that at every point (before and after an operation involving a mutex semaphore) all the values of the different `count` variables are identical. These mechanisms are presented in details in the following subsection followed by an example of their implementation.

5.2.1 Voter Mechanism

The voting mechanism is made by introducing a function to the system that has been called `vote_mutex()`. This functions receives a pointer structure to the mutex which has to be voted upon, and then performs a bitwise voting operation.

```
int vote_mutex(struct mutex *lock){
  votetrv=((c&c1)|(c&c2))|(c1&c2);
  atomic_set(&lock->count,  votetrv);
  atomic_set(&lock->count1, votetrv);
  atomic_set(&lock->count2, votetrv);
  return   votetrv;
}
```

Where:

- `atomic_set(L,V)` is a function that saves the value `V` at location `L`
- `votetrv` is the vote result
- `c` is an `atomic_read(&lock->count)`
- `c1` is an `atomic_read(&lock->count1)`
- `c2` is an `atomic_read(&lock->count2)`
- `atomic_read(L)` is a function that returns the value stored at location `L`.

Following the bitwise voting operation, every single counter variable is updated. Then the function returns the value of the vote (`votetrv`). In this way, the value can be used as an input argument in functions that require information about the current status of the semaphore.

It is important to note that because the voter function, `vote_mutex()`, is implemented before all operations made into the `count` variable, then any modification exclusively in `count` would be the equivalent of performing an operation in the voter result.

5.2.2 Mutex Update

The counter variables update mechanism are made in two different ways. The first way is by implementing a function named `mutex_update_value()`. This function is called right after a modification of `count` variable is made, provided that the functions modifying the value of `count` did not allow the usage of `count1` and count2 directly: this is common for architecture dependant functions. This function is defined as follows.

```
 void mutex_update_value(struct mutex *lock){
atomic_set(&lock->count1,
 atomic_read(&lock->count));
atomic_set(&lock->count2,
 atomic_read(&lock->count));
}
```

This function was implemented immediately after every function that does not support operations over count1 and count2. mutex_update_value() reads the value of count and updates it directly into count1 and count2.

The second way is by means of additional identical functions that operate with the count variable using the other two newly introduced variables. This kind of update mechanism is implemented when there are no limitations to the operation over count1 and count2: this is particularly true when performing logic operations.

5.2.3 Implementation Examples

An example of the application of the voter and the first update mechanism can be seen in the following example.

```
void __sched mutex_lock(struct mutex *lock)
{
might_sleep();
vote_mutex(lock);
/*
 * The locking fastpath is the
 * 1->0 transition from
 * 'unlocked' into 'locked' state.
 */
__mutex_fastpath_lock(&lock->count, __mutex_lock_slowpath);
mutex_update_value(lock);
mutex_set_owner(lock);
}
```

In the presented example, it is possible to observe the `mutex_lock` function. The voter is used right before `__mutex_fastpath_lock` because this function will read the value of the mutex lock and then decide whether to execute a fastpath or a slowpath lock. During `__mutex_fastpath_lock` a decision is made to decrease the value of count from 1 to 0 or to call the function `__mutex_lock_slowpath` depending on the value of `count`. Following the decision, it is necessary to implement `mutex_update_value()`, independent of the decision made by `__mutex_fastpath_lock` to run slowpath or not, the value of count has changed, and given that `__mutex_lock_slowpath` is a long process, it is not efficient to triplicate its execution due to the excessive overhead it would produce.

An example of the second update mechanism can be seen in the following line extracted from the function `__mutex_lock_common`:

```
static __always_inline int __sched
__mutex_lock_common(struct mutex *lock, long state, unsigned int
 subclass, struct lockdep_map *nest_lock, unsigned long ip,
    struct ww_acquire_ctx *ww_ctx, const bool use_ww_ctx)
{
...
for (;;) {
...
votetrv = vote_mutex(lock);
if  ((votetrv >= 0 ) &&
(atomic_xchg(&lock->count, -1) == 1)
&&
(atomic_xchg(&lock->count1, -1) == 1)
&&
(atomic_xchg(&lock->count2, -1) == 1))
{
break;
}
...
```

In this example atomic_xchg saves the value -1 into count variables and then returns the previous values of the count variables in order to make a decision. Because atomic logic operation are being used, it is more efficient to implement this atomic operation in every single one of our custom count variables.

5.3 Experimental Results

In order to evaluate the effectiveness of the proposed solution, a series of experiments were conducted.

5.3.1 Experimental Set-up

Four distinctive scenarios were considered for this experimental campaign: all experiments consisted in evaluating the performance of different benchmarks running in the Linux kernel. Two different operating systems were used in the tests: the first was a stable version of the Linux kernel running version 4.2 and the second was a custom robust version of kernel 4.2 which used the modifications previously discussed in this chapter. Additionally, some versions of the experiments had a single bit flip fault injected in memory using the fault injector described in chapter 3. The scenarios considered are the following:

- Golden Experiment (a): The stable version of the Linux kernel running the benchmarks and providing a reference performance value.
- Robust system (b): Evaluation of the impact caused by the robustness modifications made to the kernel in terms of performance of the benchmarks programs.
- Control FI (c): Equivalent to (a) with the difference that a single bit flip operation is performed at a random time during the operation of the benchmark program.
- Robust Evaluation (d): Equivalent to (b) with the difference that a single bit flip operation is performed at a random time during the operation of the benchmark program.

Table 5.1 reports a classification of the different experimental scenarios.

Table 5.1 Scenarios for the experimental campaign

OS Version	Without FI	With FI
Stable OS	Control Experiment(a)	Control FI(c)
Robust OS	Robust Operations(b)	Robust Evaluation(d)

The considered benchmarks were the same considered in section 4.4. These benchmarks are the following:

- IOzone3 [48]
- Netperf [48]
- Matrix product (MP)
- GZIP.

All benchmarks were individually tested. All experiments were executed in virtual machines using VirtualBox version 5.0.14. The host machine ran a Linux Kernel version 4.2 stable. While the virtual machines were running a Linux kernel version 4.2 stable on scenarios (a,b) and a custom robust version 4.2 for (c,d). Experiments (a,b) were made 20 times, providing an average of the performance for each one of the benchmarks. Tests (a) and (b) were repeated in virtual machines provided with 3 cores; while in (c,d) the experiments were made by injecting in the most and least significant bits of each one of the `count` variables of every mutex in the system.

5.3.2 Performance Results Analysis

The performance of scenarios (a) and (b) showed an overall loss of performance in accordance with table 5.2. The performance measurement of IOzone is expressed in I/O operations per second, while the performance measurement of Netperf is expressed TCP transactions per second. In the other hand, the performance measurement both of the Matrix Product and GZIP benchmarks are taken from the real elapsed time for completion in seconds using the `time` command.

Table 5.2 Performance overhead analysis

Benchmark	Standard OS	Patched OS	% Loss
IOzone3	433017.65	427882.05	1.19%
Netperf	21944.01	21626.52	1.44%
MP	38.93	38.97	0.10%
Gzip	46.02	46.20	0.39%
Average			0.78%

Given the distribution of the results from the experiments we can infer that CPU bound applications could have a smaller overhead than I/O bound applications.

5.3.3 Fault Effect Results Analysis

As described in section 4.7, faults into the mutex semaphores present observable effects.

Table 5.3 presents the distribution of the results obtained from the experimental tests considering scenarios (c) and (d). Change in the most and least significant bits present the most critical results as in accordance with the results presented in section 4.7. The novelty is that the operating system with the robust source files is able to detect and correct the faults, thus proving that a TMR-like approach on the count variable of the mutex data structure could add robustness to the operating system.

In section 4.7 it was reported that some faults injected into the mutex propagated from operating system to the Netperf benchmark program. These faults prevented the generation of Netperf's server-client connection, but the operating system continued to operate normally. In the current experimental tests running in the standard kernel such faults were present in 4.8% of the faults. While in the robust kernel version this fault propagation did not take place, meaning that 100% of the experiments that would have presented such failure were corrected by the the robust OS.

Table 5.3 Fault Injection Experimental Results.

IOZONE

Scenario	#FI	POF	SHPO	SDPO	BUI	BS
Standard(c)	372	6	21	14	1	4
Patched(d)	372	0	0	0	0	0

NETPERF

Scenario	#FI	POF	SHPO	SDPO	BUI	BS
Standard(c)	372	7	14	13	1	5
Patched(d)	372	0	0	0	0	0

MP

Scenario	#FI	POF	SHPO	SDPO	BUI	BS
Standard(c)	372	5	17	16	1	4
Patched(d)	372	0	0	0	0	0

GZIP

Scenario	#FI	POF	SHPO	SDPO	BUI	BS
Standard(c)	372	3	18	15	1	4
Patched(d)	372	0	0	0	0	0

5.4 Process Synchronisation

As described in chapter 2, the *scheduler* is the entity that is responsible for synchronising and switching from one process to the next. Additionally, in sections 4.6 and 4.7 the susceptibility to faults in the following fields of this data structure has been demonstrated:

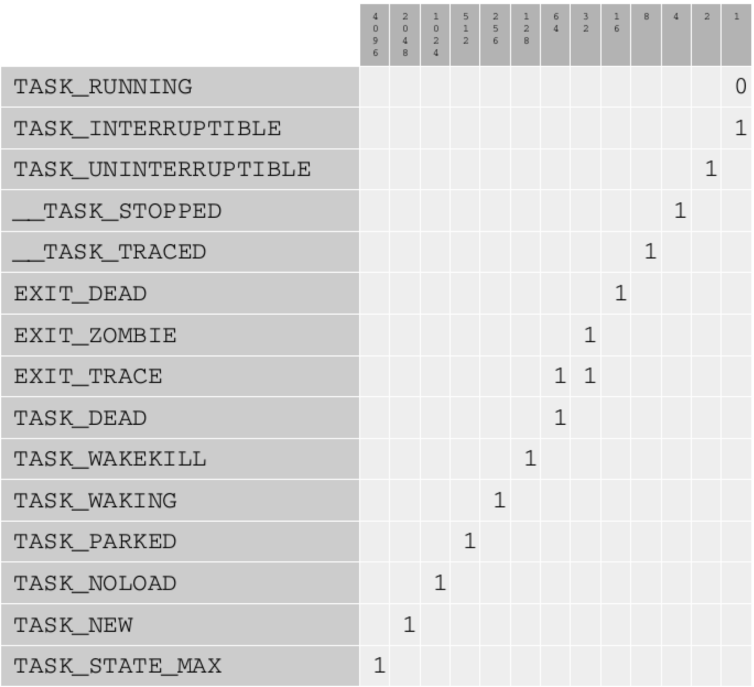
- `state`
- `thread_info->flags`
- `prio`

All these fields contained bits that proved to be critical as far as dependability is considered, therefore a redundant mechanism is needed in order to detect and correct faults affecting these mechanisms.

5.4.1 Redundancy Method

This section focused in the possible implementation of an hardening approach based in encoding of the information storage. This redundancy would be made to solve the issues generated by faults in the `state` field of the `task_struct` [50]. This approach is based in the duplication of information and the modification of the encoding mechanism of this variable so that it becomes possible to detect and correct the faults.

As described in chapter 2, the `state` is the field that informs the scheduler which is the current status of the process. This state is defined in a bitmap like manner, meaning that a value of one in each bit corresponds to a particular state. From the results reported in section 4.6 and 4.7 most of the faults occurred when the fault managed to make the switch from one state to another valid state, rather than to an invalid state (a state not defined in the bit map). The possible states are defined as described in Figure 5.3. There are also other states that are defined as an `or` operation between two or more single bit states. In Figure 5.3, we can observe the example of `EXIT_TRACE`, being a state defined by 1 in two different columns. All the other multiple bit states are defined with the prefix `TASK_` and then the following names: killable, stopped, traced, idle, normal, all and report.



	4096	2048	1024	512	256	128	64	32	16	8	4	2	1
TASK_RUNNING													0
TASK_INTERRUPTIBLE													1
TASK_UNINTERRUPTIBLE												1	
__TASK_STOPPED											1		
__TASK_TRACED										1			
EXIT_DEAD									1				
EXIT_ZOMBIE								1					
EXIT_TRACE							1	1					
TASK_DEAD							1						
TASK_WAKEKILL						1							
TASK_WAKING					1								
TASK_PARKED				1									
TASK_NOLOAD			1										
TASK_NEW		1											
TASK_STATE_MAX	1												

Fig. 5.3 Original definition of the state fields values.

In order to achieve redundancy, two steps are needed. The first is the duplication of the elements of the state field with an offset of 32 bits in the following way:

$$\text{State} = 2^n \rightarrow 2^{32+n} + 2^n$$

In this way we can obtain a variable that is divided in two with each part indicating the current state of the process. This would allow to recognize when there is a faulty state in any of the parts given that both parts should have the same values with at most one corrupted bit value. This is generally true to every case except for any fault that makes a change from or to a multi bit state, such as a fault affecting the EXIT_TRACE state. In this case we are able to detect all faults and correct most of the faults. The duplication step allows the detection of faults, provided that only one of the sides presents a valid state. Additionally, it is possible to correct the fault by updating the value of the state with the valid state. The only case in which this is not possible is when the bit indicating the state is affected with a single fault resulting in a value of zero in one half and another state field in the other half, and this would cause to have two valid states with the state value of 0 corresponding to TASK_RUNNING. These examples can be seen in Figure 5.4, a) shows what the implementation of simple

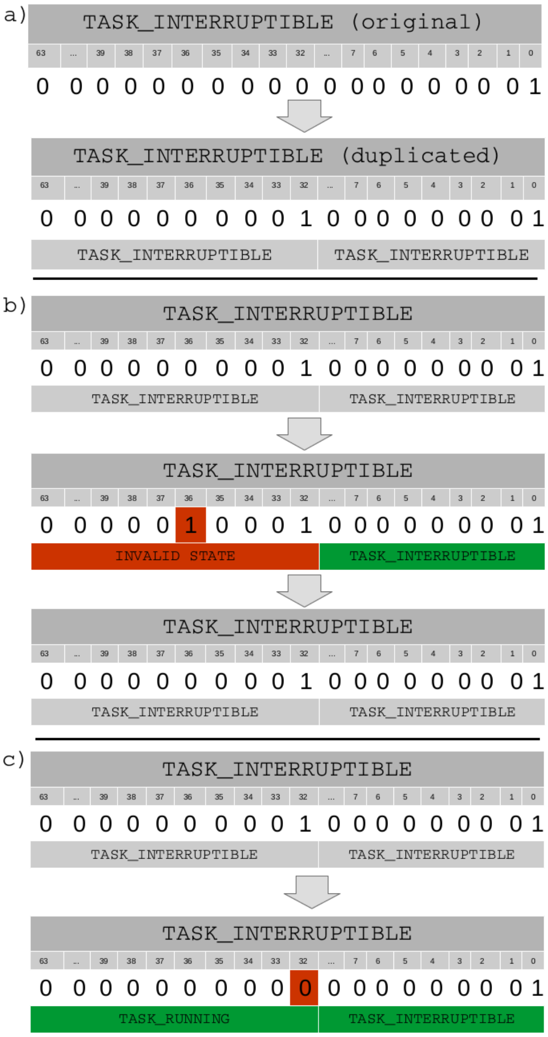
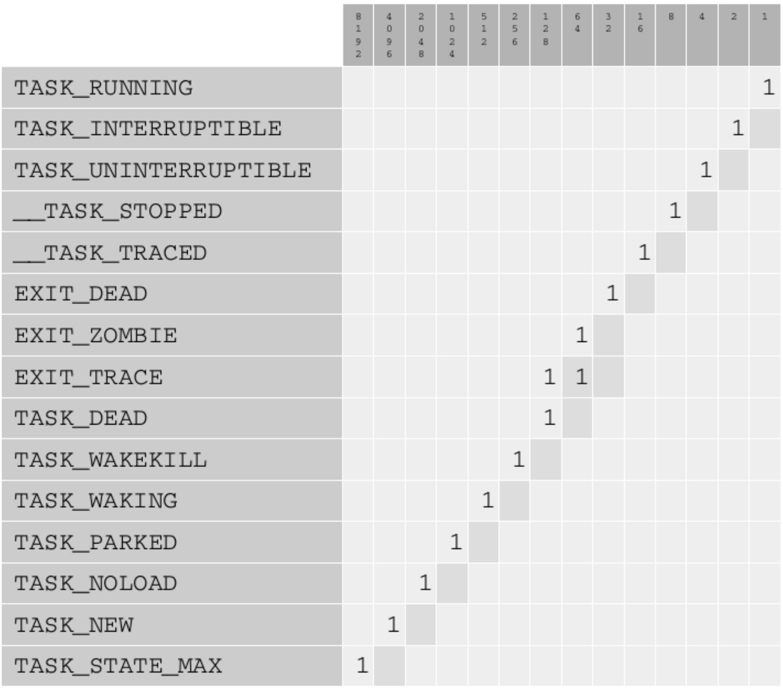


Fig. 5.4 a) Duplication of the state field values. b) Detection and correction of a single fault in the new duplicated value. c) Problem with the modification resulting in a `TASK_RUNNING` value.



	8192	4096	2048	1024	512	256	128	64	32	16	8	4	2	1
TASK_RUNNING														1
TASK_INTERRUPTIBLE													1	▨
TASK_UNINTERRUPTIBLE												1	▨	
__TASK_STOPPED											1	▨		
__TASK_TRACED										1	▨			
EXIT_DEAD									1	▨				
EXIT_ZOMBIE								1	▨					
EXIT_TRACE							1	1 ▨	▨					
TASK_DEAD							1	▨						
TASK_WAKEKILL						1	▨							
TASK_WAKING					1	▨								
TASK_PARKED				1	▨									
TASK_NOLOAD			1	▨										
TASK_NEW		1	▨											
TASK_STATE_MAX	1	▨												

Fig. 5.5 Final values for each half of the variables for the proposed redefinition of the `state` field. In darker gray the original values.

duplication would look like, while in b) shows how an error in one of the halves of the new state field would be detected, while c) demonstrate the issue when one of the halves is or becomes `TASK_RUNNING`.

The second step necessary to ensure a robust `state` field is a shift left operation in every state, thus assuring that state 0 corresponds to an invalid state. By doing this, each state cannot be modified to another valid state with a single fault, except for `EXIT_TRACE`. The new definition for the `state` field should then be as follows:

$$\text{State} = 2^n \rightarrow 2^{32+n+1} + 2^{n+1}$$

The final definition of the state fields variable would be as presented in Figure 5.5. Given the implementation of these two steps it is possible to detect and correct most faults affecting the state field. For fault generating changes to `state` from and to multiple bit states we can only detect faults. Additionally, extensive modification to the scheduler have to be made in order to read and update the correct values of the new state fields.

Chapter 6

Conclusions

This research project had two main objectives, the first is to evaluate the effects of faults in the different kernel data structures, and the second objective is to add redundancy techniques to these structures.

The first objective was achieved, and the proposed fault injection module proved to be capable of generating faults in a diverse number of elements in the kernel, demonstrating that faults affecting these data structures are critical as far as dependability is considered. In theory KITO should be able to inject transient faults in any memory element of the kernel space of the operating system.

During the experimental campaigns, it was proven that faults in some elements of the operating system can alter the operation of the operating system and in some cases also the operation of the applications that depend in the support of the different services provided by the operating system.

In relation to the second objective, it was demonstrated that a TMR-like approach in the mutex data structure is capable of providing sufficient protection to detect and correct faults affecting the `count` variable of this structure. The experimental evaluation of the proposed method for the hardening of the `state` field of the process control block is still pending.

Overall the main objective of generating a fault injection method in order to evaluate the criticality of the kernel data structures was achieved. Meanwhile the protection of the elements of the kernel that have been proven critical has been partially achieved.

From the implementation of this method in different versions of the Linux kernel it is clear that this method has a high degree of portability. It remains to be seen if this is true in the case of different operating systems based in the Linux kernel or micro kernel such as OSX, Solaris, QNX or Yocto project applications. OSX is the operating system implemented in all Apple devices. While Solaris is a Linux distribution developed by Sun Microsystems which is commonly implemented in network servers. QNX is an Real Time Operating System (RTOS) for embedded application, commonly found in automotive applications. Yocto Project is an open source micro kernel developed from OpenEmbedded. Future activities could apply the proposed hardening techniques for these real-time and embedded systems, along side exploring different data structures or memory elements of mechanisms that were not included in this research activity. Such elements include such as the `thread_struct`, RCU mechanisms, shared memory, call systems messages, etc.

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Appendix A

The KITO Module

```
#include <linux/module.h>
#include <linux/moduleparam.h>
#include <linux/kernel.h>
#include <linux/init.h>
#include <linux/stat.h>
#include <asm/bitops.h>
#include <linux/hrtimer.h>
#include <linux/ktime.h>
#include <linux/kallsyms.h>
#include <linux/string.h>
#include <linux/binfmts.h>
#include <linux/personality.h>
#include <linux/sched.h>

MODULE_LICENSE("GPL");
MODULE_AUTHOR("B. Montrucchio, M. Rebaudengo, A. Velasco");

//static unsigned long Baddress;

//------ definition of loading parameters ------

static unsigned long address, timensecs = 0;
const char* sym = "null_empty";
```

```
static int debug = 1, scenario = 0, testbit = 0;
static long timesecs = 0;
static int pid = 1;

ktime_t ktime;
long delay_in_secs;
unsigned long delay_in_ns;

//-------------------------------------
static unsigned long *FITaddress;
//pointer to the Fault Injection Target (FIT)
static unsigned long VOTaddress;  //Value Of Target



//===== LOADING PARAMETERS =====
module_param(pid, int, 1);
MODULE_PARM_DESC(pid, "PID of the task to be modified");
module_param(scenario, int, 0);
MODULE_PARM_DESC(scenario, "Scenario to be executed, 0 for address \
(default), 1 for Kernel Symbols, 2 for a task Process control Block");
module_param(address, ulong, 0);
MODULE_PARM_DESC(address, "Address to be modified");
module_param(sym, charp, 0);
MODULE_PARM_DESC(sym, "Name of a symbol to be modified");
module_param(testbit, int, 0);
MODULE_PARM_DESC(testbit, "Bit to be modified");
module_param(timesecs, long, 1);
MODULE_PARM_DESC(timesecs, "Time in seconds");
module_param(timensecs, ulong, 0);
MODULE_PARM_DESC(timensecs, "Time in nanoseconds");
module_param(debug, int, 1);
MODULE_PARM_DESC(debug, " 0 to turn off dmesg");

//===== "ATOMIC" OPERATION =====
static struct hrtimer hr_timer;

enum hrtimer_restart fi_hrtimer_callback( struct hrtimer *timer )
{
change_bit(testbit,FITaddress); //change of the bit
if (debug == 1 )
{
VOTaddress = *FITaddress;
printk(KERN_INFO "After the fault injection the value is %d\n", VOTaddress);
printk(KERN_INFO "=============================\n");
}
return HRTIMER_NORESTART;
}


//===== MODULE IN & OUT FUNCTIONS =====

//init of the kernel mod

static int __init chgbittest_init(void)
{
if (scenario == 0){ // If for modifying a particular Address in memory
if (address !=  0)
{
FITaddress = address;
VOTaddress = *FITaddress;
if (debug == 1)
printk(KERN_INFO "The value of the loaded address is %lu\n", address);
printk(KERN_INFO "At first value is %d\n", VOTaddress);
printk(KERN_INFO "=============================\n");
}
else
{
printk(KERN_INFO "No loadable values given, cannot proceed\n");
return 0;
}
printk(KERN_INFO "Scenario 0 Fault Injection in a particular address\n");
}


if (scenario == 1){ // IF for modifying a exported kernel symbol
if (sym != "null_empty")
{
FITaddress = kallsyms_lookup_name(sym);
VOTaddress = *FITaddress;
if (debug == 1)
printk(KERN_INFO "The value of the symbol's address is %lu\n", FITaddress);
printk(KERN_INFO "At first value is %d\n", VOTaddress);
printk(KERN_INFO "============================\n");
}
else
{
printk(KERN_INFO "No loadable values given, cannot proceed\n");
return 0;
}
printk(KERN_INFO "Scenario 1 Fault Injection in a Kernel Symbol\n");
}
if (scenario == 2){ // If for modifing the task struct
struct task_struct *t = pid_task(find_vpid(pid),PIDTYPE_PID);
//Get task pointer struct
VOTaddress = (*t).state; //MODIFY TO DESIRED FIELD AND RECOMPILE
FITaddress = &((*t).state); //MODIFY TO DESIRED FIELD AND RECOMPILE
if (debug == 1){
printk(KERN_INFO "Field value is %d\n", VOTaddress);
printk(KERN_INFO "Field address is the value is %lu\n", FITaddress);
printk(KERN_INFO "============================\n");
}
printk(KERN_INFO "Scenario 2 Fault Injection in a field of the
Task_struct of a particular process\n");
```

```
}



printk(KERN_INFO "=============================\n");

//===== TIMER =====

delay_in_secs = timesecs; // set the delay on seconds
delay_in_ns = timensecs; // set the delay on nseconds
ktime = ktime_set( delay_in_secs, delay_in_ns );
// set the timer with the values of delays
hrtimer_init( &hr_timer, CLOCK_MONOTONIC, HRTIMER_MODE_REL );
//init timer
hr_timer.function = &fi_hrtimer_callback;
// function to exec after timer ends
if (debug == 1){
printk(KERN_INFO "timer set to %ld s %lu ns at the CPU time %lu\n",\
delay_in_secs,delay_in_ns, jiffies );
}
hrtimer_start( &hr_timer, ktime, HRTIMER_MODE_REL );
//timer start
return 0;
}

static void __exit chgbittest_exit(void)
{
printk(KERN_INFO "FIN\n");
return;
}

module_init(chgbittest_init);
module_exit(chgbittest_exit);
```

Appendix B

Doctoral Period's Publications

2014

Software-implemented Fault Injection in Operating System Kernel Mutex Data Structure
B. Montrucchio, M. Rebaudengo, A. Velasco
5th IEEE Latin American Symposium on Circuits and Systems, Santiago, Chile, February 25-28, 2014

Fault Injection in the Process Descriptor of a Unix-based Operating System
B. Montrucchio, M. Rebaudengo, A. Velasco
IEEE International Symposium on Defect and Fault Tolerance in VLSI and Nanotechnology Systems, Amsterdam, Netherlands , 1-3 October 2014

2015

On gait recognition with smartphone accelerometer
R. Ferrero, F. Gandino, B. Montrucchio, M. Rebaudengo, A Velasco, I. Benkhelifa
4th Mediterranean Conference on Embedded Computing (MECO-2015), Budva, Montenegro, 14-18 June, 2015

On the design of distributed air quality monitoring systems
R. Ferrero, F. Gandino, B. Montrucchio, M. Rebaudengo, A Velasco
11th International Conference of Computational Methods in Sciences and Engineering (ICCMSE 2015), Atene, Greece, 20-23 March 2015

2016

KITO tool: A fault injection environment in Linux kernel data structures
B. Montrucchio, M. Rebaudengo, A. Velasco
Microelectronics Reliability, vol. 60, pp. 153-162, 2016

A mobile and low-cost system for environmental monitoring: a case study
R. Ferrero, F. Gandino, B. Montrucchio, M. Rebaudengo, A Velasco
Sensors, vol. 16 n. 5, pp. 1-17, 2016

2017

TMR Technique for Mutex Kernel Data Structures
B. Montrucchio, M. Rebaudengo, A. Velasco
18th IEEE Latin American Test Symposium, Bogota, Colombia, 13-15 March 2017

Hardening Approach for the Scheduler’s Kernel Data Structures
B. Montrucchio, M. Rebaudengo, A. Velasco
13th Workshop on Dependability and Fault Tolerance, Wien, Austria, 3-6 April 2017