Multi-layered System Robustness Testing Strategy Based on Abnormal Parameter

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Abstract—**A multi-layered fault injection mode is explored and a multi-layered system robustness testing strategy based on abnormal parameter is put forward. Fault injection methods for three layers (API, DPI and system calls based on workloads) of Linux operation system are designed. And an integrated fault injection platform to multi-layered fault injection for testing robustness of operating system is implemented. Using the multi-layered system robustness testing strategy based on abnormal parameter under the platform, various layers of system robustness evaluation are achieved. Finally, the results under different layers of fault injection are compared and analyzed in order to evaluate the robustness of target system.**

Index Terms — **abnormal parameter, fault-injection, multi-layered robustness testing**

I. Introduction

System robustness is a measure of the ability to maintain a normal condition in the environment of abnormal input or pressure system [1], reflecting the system's detection and processing capabilities for failures, external events and system maintenance events. In critical industrial applications, system delays and failures may cause incalculable damage, so under the premise to ensure the system's high-performance transaction processing capabilities, the system's robustness is essential.

Robustness test is a more emerging area of research, the study of this topic focused on some foreign universities. Professor Miller of University of Wisconsin proposed by means of fault injection to evaluate the system robustness earlier. Professor Siewiorek of Carnegie Mellon University proposed the definition of robustness testing benchmark to test system handling error input or unexpected input in different levels, distinguish robustness testing and traditional performance testing for the first time; Professor Koopman described a portable testing benchmark to test the robustness of UNIX operating systems, and proposed an approach to classify the testing results and compare between different operating systems. Mukherjee and Siewiorek proposed a hierarchical approach to building robust testing benchmarks [2].A workload-aware reliability evaluation model is introduced in [3].

In recent years, software testing technology has developed rapidly, a large number of software testing tools are developed, the tools for system robustness testing are more and more, and they can automatically detect software failures, and find a large number of software failures and security risks in some large commercial software and open source software testing. A failure detection scheme in order to improve the fault tolerance of the service is proposed in [4]. EXPLODE found a number of serious problems in some common file storage systems; MC found nearly 500 faults and more than 100 security vulnerabilities in Linux, OpenBSD and other software; SDV found 65 faults, including 12 serious software failure in the test of drivers of Windows operating system, etc.[5].

Although there have been a lot of study results of fault injection, and many fault-injection tools have been used, the research of fault injection techniques for the unity of its own formal model is still lacking [6].Most researches have focused on two aspects:

1) Improvement and innovation to the concrete realization of fault injection, including the methods injecting faults to different abstraction levels, simulating the real fault impact as accurately as possible, improving the trigger accuracy of fault injection, reducing overhead and improving accuracy of testing results, etc.;
2) Fault injector designed for certain specific projects, which aims to get some interesting characteristics or indicators through fault injection to a specific system. The research limitations led to these specific fault injection techniques simple rather than system application.

All in all, the traditional fault injection tools are often designed to assess a target system, limited to a specific architecture, and fault injection method simple, such as early fault injection tools FIAT, FERRARI, etc.; recent years, the study of fault injection began to develop to the

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multiplex direction, many new fault-injection tools integrate a variety of fault-injection techniques and can be transplanted between multiple operating systems, such as integrated fault injection tool GOOFI [7], which combines four fault injection means, including software fault injection, scan chain implemented fault injection, through the on-chip debug interface fault injection and standard interface fault injection.

Table 1 compared the characteristics of the classic robustness testing tools:

TABLE 1
PERFORMANCE COMPARISON FOR A VARIETY OF ROBUSTNESS TESTING TOOLS

Tool	Portability	Coverage	Scalability	Level of detail	Repeatability
Crashme	Good	Low	Bad	Low	Low
FIAT	Bad	High	Bad	High	Low
FUZZ	Good	Low	Good	Low	High
Ballista	Good	High	Good	High	High
FINE	Good	High	Bad	High	High

We can see Ballista has the advantages of portability, high test coverage, scalability, high level of detail, and good repeatability. And Ballista has high degree of automation and tests software without source code. Nevertheless, Ballista only calls API functions in user mode frequently, causing the user-level failures, can’t trigger kernel-level failures, and not consider the workload running on the system, the robustness testing of the system is not entire.

Utilizing thoughts of injecting abnormal parameters to the interface functions, integrating the classic abnormal parameter injection methods and a variety of fault injection strategies of dynamic and static, user mode and kernel mode, this paper proposed a multi-layered system robustness testing strategy based on abnormal parameters for the architecture of Linux operating system, using a consistent fault injection method to the different levels of fault injection, testing system programming interface robustness in user mode and kernel mode, and system robustness of dynamic load. As robustness testing results are produced from the consistent fault injection strategy, so that different levels of the test results have good comparability.

II. MULTI-LAYERED FAULT INJECTION STRATEGIES BASED ON ABNORMAL PARAMETERS

According to the process system provide service mode to user process, system can be divided into three levels: user programming interface layer, the system call layer and the core function layer. Thus, to provide services, the system robustness failures can be attributed to these three levels, a certain level of testing which can test system robustness from a certain point, but it is incomplete. The multi-layered system robustness testing strategy based on abnormal parameters integrates the classic method of abnormal parameters and the dynamic and static, user mode and kernel mode for a variety of fault injection strategies, uses the consistent fault injection method to different levels of system, and tests system robustness of user mode and kernel mode programming interface and dynamic load of the system.

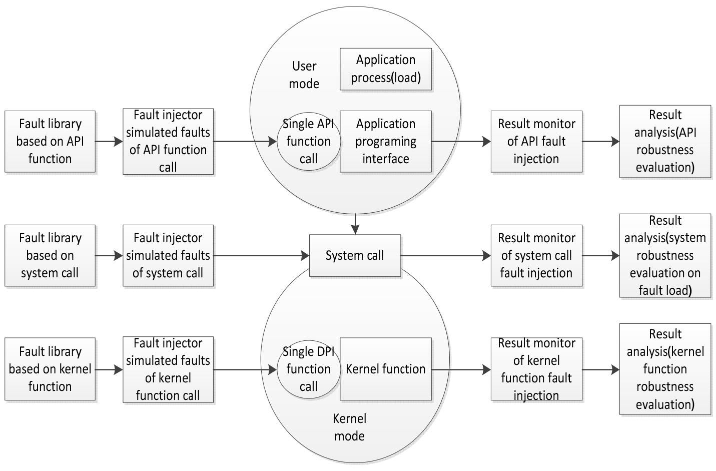

User mode
Application process(load)
Fault library based on API function
Fault injector simulated faults of API function call
Single API function call
Application programing interface
Result monitor of API fault injection
Result analysis(API robustness evaluation)
Fault library based on system call
Fault injector simulated faults of system call
System call
Result monitor of system call fault injection
Result analysis(system robustness evaluation on fault load)
Fault library based on kernel function
Fault injector simulated faults of kernel function call
Single DPI function call
Kernel function
Result monitor of kernel function fault injection
Result analysis(kernel function robustness evaluation)
Kernel mode

Figure 1 Fault injection strategy of multi-layered system robustness testing

A. Fault Injection Strategy of User Mode and Kernel Mode

1. Fault parameters generated

The fault injection objects to test API robustness are API function calls in line with the POSIX standard [8]. The fault injection objects of DPI robustness testing are the commonly used DPI function calls compatible with some target systems [9], including C library functions of the core API, memory management functions, etc.

Fault parameters generating process:

```
1) fault_line = grep ($ function, list) //match the
   function name, get the function information of
   the list;
2) if (no matching information) {the function is
   not the injecting object};
3) @params = split(fault_line) //get the type of
   fault parameters of the function @ params;
4) ./paramGen @params //generate the fault
   parameters set of use cases corresponding to
   parameter type;
5) Sequentially select a set of fault parameters
   fault_params;
6) ./inject function fault_params //perform fault
   injection.
```

2. Fault injection method

Robustness testing of API layer through abnormal parameters fault injection to a single API function calls, the injection process is:

```
1) initialize use cases of fault parameter,
   perform the corresponding functions
   generating the fault parameters, and return the
   address of the abnormal parameters;
2) call the test functions after the first step
   generating the abnormal parameters, record
   call results when the function return value is
   not empty or structure type;
```

3) Release the resources use cases applied to construct parameters, construct clean 'environment' for the next fault injection.

Because the fault injection of API interface is function call based on the user mode, only lead to user state failure, the thinking of abnormal parameters is used to kernel functions, inject fault parameters to the driver programming interface (DPI) compatible in target systems, trigger a kernel-level failure, further test the system robustness.

Fault injection is implemented through system calls written by ourselves. Specific process is:

1) match the kernel module file ModuleSyscall.c for the tested Kernel function (the module implements the system call SYS_kernelfunc to call the objective function);
2) Compile the kernel module to get ModuleSyscall.o;
3) Insert kernel module;
4) Hook system calls;
5) Initialize the fault parameters of the objective function;
6) Pass the initialized fault parameters to the kernel space by executing the system call, test the kernel function, and return the function returned values to the user state;
7) Finally, clean up the resources the initialization applied;
8) Unload kernel modules.

B. Fault Injection Strategy of Application Load Running

According to system call's functions, the fault injections intercepted system calls are divided into four categories:

1) The system calls for file operations
2) The system calls for process control
3) The system calls for system signal
4) The system calls for disk read and write

Fault injection object on the application load is a set of a certain type of system calls of the four categories above.

1. Fault parameters generated

Because it is the runtime fault injection, this part of the fault parameters generation in addition to the method of abnormal parameters, also takes into account the most common type of fault in the actual operation: bit flip fault.

The selection of abnormal parameters refer to the statistic results of the system robustness failure causes of ballista project, statistics show that six categories of abnormal parameters caused the highest probability of system robustness failure, they are as follows: illegal file pointer (not including the empty file pointer), an empty file pointer, illegal buffer pointer (excluding empty cache pointer), an empty cache pointer, the smallest integer value, the maximum integer value [10].

Bit flip faults can be classified according to the bits damaged: single bit flip, two bits (compensation) flip and the whole word (32 bits) flip.

By flipping can be divided into: inversion, set 0 and set 1.

Fault parameters can choose the Cartesian product of the above types, also can randomly generate 32-bit mask, which and the original parameter values.

2. Runtime fault injection method

The fault injection to the system call called in the load is carried out in the load running, in Linux operating environment, to achieve fault injection to the running process, we need control the running process, read and write the process context. This paper uses system call **ptrace** to achieve the target process tracking, set traps, read the context, fault injection and result monitoring. **Ptrace** can intercept and modify the user level system calls, using **ptrace** system call, a process can dynamically read and write memory image and register values of another process, including the code segment, data segment and stack segment; and access and modify the general registers and special registers.

Runtime fault injection process is:

1) debugger forks a child process **pid = fork()**;

2) The child process calls the system call **PTRACE_TRACEME**, the result is: the kernel set a trace bit in the child process table, requiring the parent process trace into debug state;

3) The child process executes the tracked program, i.e. the work load. Kernel executes the system call **exec(workload)**, when execution to the last, due to the track bit is set, sends a soft interrupt signal **SIGTRAP** to the child process;

4) When the system call **exec(workload)** returns, check the soft interrupt signal. If the tracking bit is set in the process table, the child process wake up the parent process slept in the system call **waitpid**, into a tracking state similar to sleep state, and complete the context switch [11].

Meanwhile, the parent process executes the system call **waitpid()**, wait for the wake-up by the child process. When the child process wake up the parent process, the parent process returns from **waitpid()**, begin to execute the fault injection **inject_faults()**, and then monitor the results of fault injection.

Fault injection to workload is achieved through the ptrace system call, the format as follows:

int ptrace (int request, int pid, int addr, int data);

The parameter request is an enumeration variable, its value determines the function of system calls, as shown in Table 2:

TABLE 2
PARAMETER FEATURES of PTRACE

Parameter	Feature
PTRACE_TRACEME	Process requires the parent process to track, so that the current process into debug state
PTRACE_ATTACH	Track user process
PTRACE_DETACH	Stop debugging the process
PTRACE_PEEKTEXT	Read a word of the user instruction space
PTRACE_PEEKDATA	Read a word of the user data space
PTRACE_PEEKUSR	Read a word of the user process data area
PTRACE_POKETEXT	Write a word of the user instruction space
PTRACE_POKEDATA	Write a word of the user data space

PTRACE_POKEUSR	Write some units of the user process data area
PTRACE_SYSCALL	Track system calls, continue until return from the next system call
PTRACE_CONT	Set soft interrupt number to continue to execute child process number
PTRACE_KILL	Stop child process
PTRACE_SINGLESTEP	Set capture flag, single step process
PTRACE_GETREGS	Read register data
PTRACE_SETREGS	Write register values

pid is the process number of the process tracked; addr is the read or write data’s address in the child process; and data is data values to write. When executing the system call ptrace, the kernel first test whether the process has a child process with a process identification number pid, and that the child process is in a state to be tracked, then track it using a global data structure, to transfer data between two processes, and lock the track data structures to prevent other tracking process rewriting.

3. Runtime fault injection trigger mechanism

Fault injection on the application load is different from fault injection on single function call, fault injection time need to be chosen, because the system call injected is not always the first system call of the application load, also can choose to skip the initialization phase of the process, injecting faults when the load provides services. Therefore, under certain circumstances, trigger the fault injection through the mode of fault trigger. This strategy offers two fault trigger modes: single-step trigger and time trigger.

Single-step trigger that is trigger fault injection after the process executes the specified number of steps is implemented by the function run_step(). For the specified number of instructions, each instruction is executed in the function and keep the signal lastsig before the step to continue processing.

Time Trigger that is after the program execution time exceeds the specified time (unit: microseconds) trigger fault injection. Implement by the function run_time() to complete the following tasks:

1) Register a signal SIGALRM, the signal processing function is sig_alrm(), sigalrm() will send a signal SIGTRAP to the child process wordload to interrupt the child process.

2) Get the current machine time, resume operation of the sub-process interruption caused by ptrace (PTRACE_TRACEME).

3) Generate timer interrupt, the interrupt signal is SIGALRM, then sig_alrm() will take over the operating system's handling of SIGALRM, interrupt the child process.

III. Integrated Fault Injection Platform Based on Multi-Layered Fault Injection

For Fault injection to API function calls, DPI calls and the application process, a single fault injection measure is not enough, we need to combine multi-level fault injection and multi-angle robustness testing. Based on multi-level fault injection strategies, the paper designs and implements an integrated fault-injection platform to complete evaluation of different levels of system robustness.

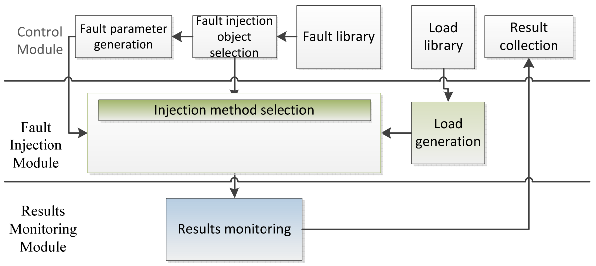


Figure 2 Integrated fault injection platform

It can be seen from Figure 2, at different levels of fault injection and results monitoring collection requires different fault injector and results monitor, fault set, fault trigger and injection strategies are different, but robust testing tools at home and abroad are basically to achieve a particular aspect of test, their architectures are not compatible, cannot construct an integrated test environment. The integrated fault-injection platform designed in this paper, whose advantage is most of the classical fault injection tools and robust testing tools can achieve compatibility in this platform through small changes, and jointly build an integrated robust test environment. In the platform, the development of robust testing tools implements the incremental development mode.

A. Control Module

Fault injection control module determines the fault injection object, generates fault parameters (fault load), and determines the application-oriented workloads.

Fault injection object: i.e. the target need fault injection. For example, fault injection to API function calls, an API function call is a fault injection object; in memory fault injection, memset1 is a fault injection object. The fault injection objects in this paper have three categories: API functions, DPI functions and the system calls in the application process.

Fault parameter generation is to generate the required parameters for the fault injection object. For example, for fault injection to the API function access, the fault parameters are a set of parameters {S1, CHAR, EMPTY, R_OK}; for the fault injection to memory fault memset1, the parameters are the memory address injected necessarily and parameter 1.

Load library is the load needed to use in fault injection, the control module designates the fault injection to the target system in which load.

Results collection module recycles the results of fault injection collected by the target system monitoring module and analyzes.

B. Fault Injection Module

Fault injection module selects fault injection method according to the fault injection object, generates the workload the control module selected, injects faults according to the fault parameters, and uses different strategies to inject faults to different levels respectively.

Injection method selection module: select the appropriate injection method for the fault injection object. For example, select the ballista tools to inject abnormal parameters for all of the API functions. The relationship between objects and methods is many to one, that is many objects may use the same injection method.

Injection method module: corresponding to different fault injection tools, injection method module selected by the injection method selection module injects faults corresponding to the parameter information in the interface information.

Load generation module: run the workload according to the type of load the control module specified.

C. Results Monitoring Module

Results monitoring module is actually the parent process executing fault injection monitors function calls or work load injected faults by the method of monitoring the child process, record the results of fault injection, and feedback to the control module for analysis. The fault injection results are divided into three categories:

Restart: process timeout restarts after fault injection;

Abort[12]: process throws an exception signal after fault-injection, causing the process to abort;

Pass: after fault injection, the process ends normally or returns the corresponding error code.

Fork child process first, implement fault injection, monitor the function call result is restart, abort or pass through monitoring the termination status of the child process[13].

Statistical analyzing the results collected by result monitoring module, results analysis module performs the following functions:

1) Read the result documents generated by result monitoring module, count the number of fault injection for each test function;
2) Read the results files, count the number of failures in fault injection and the number of the various results (pass/abort/restart) occurrences after fault injection for each test function;
3) Calculate the ratio of three outcomes (pass/abort/restart) in case of fault injection success for each function, and proportion of total failure;
4) Calculate the average failure rate of all measured functions, determine an overall robustness score.

IV. Experimental Results and Analysis

A. Robustness Testing Results of Application Programming Interface

1. Experimental Environment

Test environment I:

VMware OS: Redhat6.0 i386; kernel: Linux2.2.14; Memory: 128M; Host OS: Windows XP; CPU: AMD2800 +

Test environment II:

VMware OS: Redhat9.0 i386; kernel: Linux2.4.20; Memory: 128M; Host OS: Windows XP; CPU: AMD2800 +

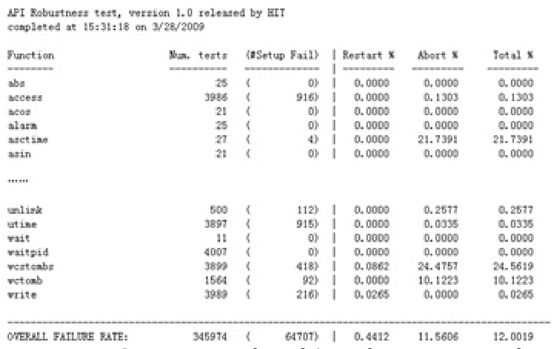
Test environment III:

OS: RHEL5.1 i386; kernel 2.6.18; Inspur server NX7140D; CPU: Intel Xeon E5405

API package is different for different versions of the Linux kernel, so API robustness is different too for different versions of the Linux operating system. The operating systems in the three experimental environments above are based on three versions of the kernel 2.2, 2.4 and 2.6 of Linux respectively.

2. Experimental results and analysis

POSIX standard API test of Redhat 6 system (Linux 2.2.14 kernel) started from 8:00 on March 28, 2009 and ended at 3:30 p.m. on March 28, 2009 (to obtain the test results). Test 213 API functions, generate 345974 test cases, of which the effective implementation of test cases 281267, each API function implemented 1320.5 effective test cases averagely. The test results are 1241 times to restart, accounting for effective test cases of 0.4412%; 32519 times to abort, accounting for effective test cases of 11.5606%; 247507 times to normally pass, accounting for effective test cases of 87.9971%.



```
API Robustness test, version 1.0 released by HIT
completed at 15:31:18 on 3/28/2009

Function                    Num. tests   (#Setup Fail) | Restart %   Abort %    Total %
--------                    ----------   ------------- | ---------   ---------  ---------
abs                                 25   (          0) |  0.0000      0.0000     0.0000
access                            3986   (        916) |  0.0000      0.1303     0.1303
acos                                21   (          0) |  0.0000      0.0000     0.0000
alarm                               25   (          0) |  0.0000      0.0000     0.0000
asctime                             27   (          4) |  0.0000     21.7391    21.7391
asin                                21   (          0) |  0.0000      0.0000     0.0000

......

unlink                             500   (        112) |  0.0000      0.2577     0.2577
utime                             3897   (        915) |  0.0000      0.0335     0.0335
wait                                11   (          0) |  0.0000      0.0000     0.0000
waitpid                           4007   (          0) |  0.0000      0.0000     0.0000
wcstombs                          3899   (        418) |  0.0862     24.4757    24.5619
wctomb                            1564   (         92) |  0.0000     10.1223    10.1223
write                             3989   (        216) |  0.0265      0.0000     0.0265

-------------------------------------------------------------------------------------------
OVERALL FAILURE RATE:           345974   (      64707) |  0.4412     11.5606    12.0019
```

Figure 3 Linux-2.2.14 kernel API robustness test results

System API functions are divided into 15 categories, including file management, directory management, process control, process scheduling, signals, semaphores, terminal I/O, advanced I/O, standard library functions, string handling, character handling, mathematical functions , time functions, memory management, and other library functions. The function failure rate according to the classification above is as follows:

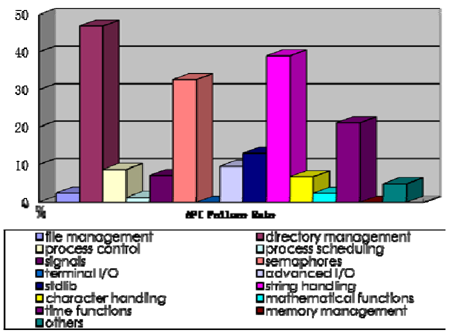
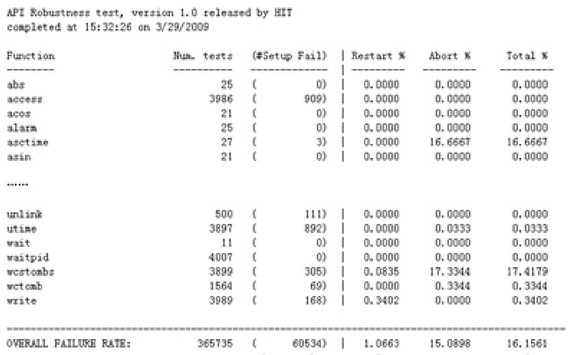


Figure 4 Linux-2.2.14 kernel API failure rate

Test 211 POSIX standard APIs of Linux 2.4.20 kernel, generate 365735 test cases, of which the effective implementation of test cases 305201, each API function implemented 1446.5 effective test cases averagely. The test results are 3255 times to restart, accounting for effective test cases of 1.0663%; 46055 times to abort, accounting for effective test cases of 15.0898%; 255891 times to normally pass, accounting for effective test cases of 83.8434%.



```
API Robustness test, version 1.0 released by HIT
completed at 15:32:26 on 3/29/2009

Function              Num. tests  (#Setup Fail) | Restart %   Abort %    Total %
--------              ----------  ------------- | ---------  ---------  ---------
abs                           25  (          0) |  0.0000     0.0000     0.0000
access                      3986  (        909) |  0.0000     0.0000     0.0000
acos                          21  (          0) |  0.0000     0.0000     0.0000
alarm                         25  (          0) |  0.0000     0.0000     0.0000
asctime                       27  (          3) |  0.0000    16.6667    16.6667
asin                          21  (          0) |  0.0000     0.0000     0.0000

......

unlink                       500  (        111) |  0.0000     0.0000     0.0000
utime                       3897  (        892) |  0.0000     0.0333     0.0333
wait                          11  (          0) |  0.0000     0.0000     0.0000
waitpid                     4007  (          0) |  0.0000     0.0000     0.0000
wcstombs                    3899  (        305) |  0.0835    17.3344    17.4179
wctomb                      1564  (         69) |  0.0000     0.3344     0.3344
write                       3989  (        168) |  0.3402     0.0000     0.3402

==================================================================================
OVERALL FAILURE RATE:     365735  (      60534) |  1.0663    15.0898    16.1561
```

Figure 5 Linux-2.4.20 kernel API robustness test results

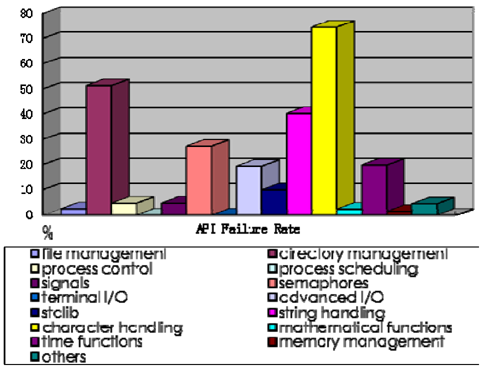
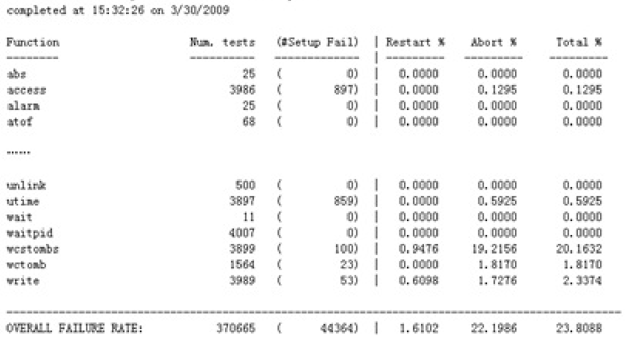


Figure 6 Linux-2.4.20 kernel API statistics of failure rate

POSIX standard API test of Redhat 5EL system (kernel version 2.6.18) started from 18:00 on March 12, 2009 and ended at 15:32 on March 30, 2009 (to obtain the test results). Test 208 API functions, generate 370665 test cases, including the effective implementation of test cases 326301, each API function implemented 1568.75 effective test cases averagely. The test results are 5253 times to restart, accounting for effective test cases of 1.61%; 72434 times to abort, accounting for effective test cases of 22.1986%; 248614 times to normally pass, accounting for effective test cases of 76.1916%.



```
API Robustness test, version 1.0 released by HIT
completed at 15:32:26 on 3/30/2009

Function              Num. tests  (#Setup Fail) | Restart %   Abort %    Total %
--------              ----------  ------------- | ---------  ---------  ---------
abs                           25  (          0) |  0.0000     0.0000     0.0000
access                      3986  (        897) |  0.0000     0.1295     0.1295
alarm                         25  (          0) |  0.0000     0.0000     0.0000
atof                          68  (          0) |  0.0000     0.0000     0.0000

......

unlink                       500  (          0) |  0.0000     0.0000     0.0000
utime                       3897  (        859) |  0.0000     0.5925     0.5925
wait                          11  (          0) |  0.0000     0.0000     0.0000
waitpid                     4007  (          0) |  0.0000     0.0000     0.0000
wcstombs                    3899  (        100) |  0.9476    19.2156    20.1632
wctomb                      1564  (         23) |  0.0000     1.8170     1.8170
write                       3989  (         53) |  0.6098     1.7276     2.3374

==================================================================================
OVERALL FAILURE RATE:     370665  (      44364) |  1.6102    22.1986    23.8088
```

Figure 7 Linux-2.6.18 kernel API robustness test results

API robustness test results of different Linux kernel versions were compared, as shown in Figure 8. We found the probability of robustness increases with the improvement of the kernel version and the gradual powerful functionality realized.

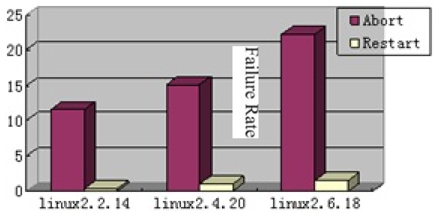


Figure 8 Test results of different Linux kernel versions

By comparing failure rate of different types of functions (file management, directory management, process control, process scheduling, signals, semaphores, terminal I/O, advanced I/O, string handling, character handling, math functions, time functions, memory management and other library function), as shown in Table 3, further analyze the reason of robustness failure rate increasing for different kernel versions.

TABLE 3
FUNCTION ROBUSTNESS FAILURE RATE FOR DIFFERENT KERNEL VERSIONS (%)

	linux2.2.14	linux2.4.20	linux2.6.18
file management	2.3895	2.4949	5.0101
directory management	46.8822	51.3514	66.1193
process control	8.7339	4.7188	16.4803
process scheduling	1.2361	0	0
signals	7.1246	4.7901	7.545
semaphores	32.6615	27.1955	28.7383
terminal I/O	0.0063	0.0063	0
advanced I/O	9.5281	19.3929	33.2777
stdlib	13.0155	9.9452	13.8521
string handling	38.9493	40.22	64.3342
character handling	6.7692	74.4615	81.2308
math functions	2.3522	2.3522	1.6529
time functions	21.1428	19.8549	20.5587
memory management	0	1.4493	2.8802
others	4.9091	4.4641	5.1048

From figure 9 can be found the increase of robustness failure probability was mainly due to the rapid increase of advanced I/O function, string handling function and character handling function. Typically in linux2.2 kernel, the robustness failure probability of fault injection to character handling function is only 6.7692%, while the failure probability of 2.4 kernel and 2.6 kernel is 74.4615% and 81.2308% respectively. The reason is mainly due to robustness failure of the high version function implementation in the wrong argument type.

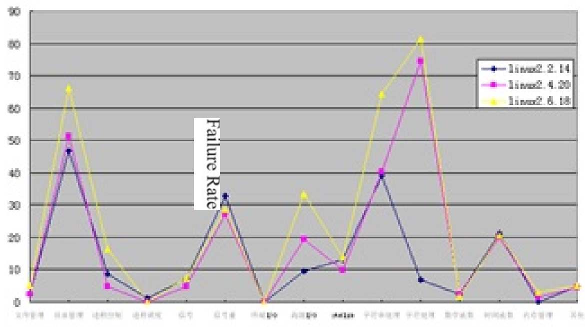


Figure 9 Comparison of failure rate of various types of functions for different Linux kernel versions

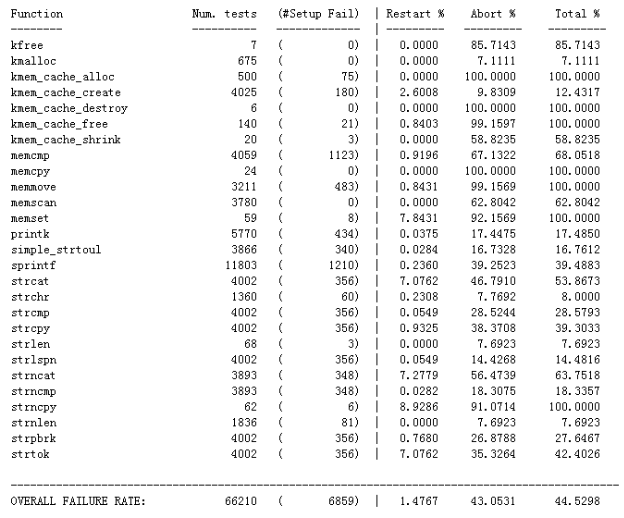
B. Robustness Testing Results of Driver Programming Interface

1. Experimental Environment

VMware OS: Redhat9.0 i386; Kernel: Linux2.4.20; Memory: 128M; Host OS: Windows XP; CPU: AMD2800 +

2. Experimental results and analysis

Figure 10 shows the robustness test results of some commonly used DPI functions. For each function to be tested, count the probability of restart, abort and pass after injecting abnormal function parameters respectively.



```
Function                Num. tests   (#Setup Fail) | Restart %   Abort %     Total %
--------                ----------   ------------- | ---------   ---------   ---------
kfree                            7   (          0) |   0.0000     85.7143     85.7143
kmalloc                        675   (          0) |   0.0000      7.1111      7.1111
kmem_cache_alloc               500   (         75) |   0.0000    100.0000    100.0000
kmem_cache_create             4025   (        180) |   2.6008      9.8309     12.4317
kmem_cache_destroy               6   (          0) |   0.0000    100.0000    100.0000
kmem_cache_free                140   (         21) |   0.8403     99.1597    100.0000
kmem_cache_shrink               20   (          3) |   0.0000     58.8235     58.8235
memcmp                        4059   (       1123) |   0.9196     67.1322     68.0518
memcpy                          24   (          0) |   0.0000    100.0000    100.0000
memmove                       3211   (        483) |   0.8431     99.1569    100.0000
memscan                       3780   (          0) |   0.0000     62.8042     62.8042
memset                          59   (          8) |   7.8431     92.1569    100.0000
printk                        5770   (        434) |   0.0375     17.4475     17.4850
simple_strtoul                3866   (        340) |   0.0284     16.7328     16.7612
sprintf                      11803   (       1210) |   0.2360     39.2523     39.4883
strcat                        4002   (        356) |   7.0762     46.7910     53.8673
strchr                        1360   (         60) |   0.2308      7.7692      8.0000
strcmp                        4002   (        356) |   0.0549     28.5244     28.5793
strcpy                        4002   (        356) |   0.9325     38.3708     39.3033
strlen                          68   (          3) |   0.0000      7.6923      7.6923
strlspn                       4002   (        356) |   0.0549     14.4268     14.4816
strncat                       3893   (        348) |   7.2779     56.4739     63.7518
strncmp                       3893   (        348) |   0.0282     18.3075     18.3357
strncpy                         62   (          6) |   8.9286     91.0714    100.0000
strnlen                       1836   (         81) |   0.0000      7.6923      7.6923
strpbrk                       4002   (        356) |   0.7680     26.8788     27.6467
strtok                        4002   (        356) |   7.0762     35.3264     42.4026

-----------------------------------------------------------------------------------------
OVERALL FAILURE RATE:        66210   (       6859) |   1.4767     43.0531     44.5298
```

Figure 10 Robustness test results for DPI

Fault injection to functions such as memcopy, memmove, memset, strcpy, kmem_cache_destroy will lead to the kernel stack fault, resulting in system crash.

From the experimental results can be seen, robustness failure of DPI level is mainly due to the operation of string and memory. The mainly failure reason is caused by illegal string pointer and buffer pointer.

C. System Robustness Testing Results of Fault Load

1. Experimental Environment

OS: RHEL5.1 i386; Kernel 2.6.18; Inspur server NX7140D; CPU: Intel Xeon E5405

2. Experimental results and analysis

Workload: DBT-5 (simulate securities company's online transaction processing)

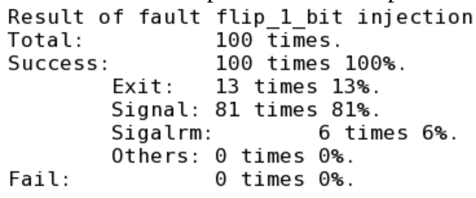
Injection timing: Skip 1000steps, skip 1000-8000 steps randomly

Fault Injection times: 100 times

Fault Response Time: 8000 mocrosecond

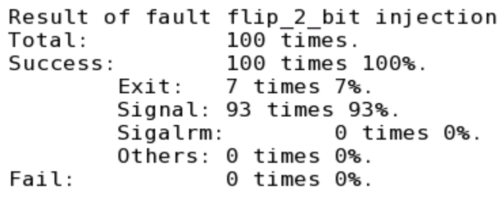
Injection object: system calls of file operations

Figures 11 and 12 are the fault injection results for the parameters of one bit flip and two bits flip.



```
Result of fault flip_1_bit injection:
Total:          100 times.
Success:        100 times 100%.
        Exit:   13 times 13%.
        Signal: 81 times 81%.
        Sigalrm:        6 times 6%.
        Others: 0 times 0%.
Fail:           0 times 0%.
```

Figure 11 Fault injection results of parameters of one bit flip



```
Result of fault flip_2_bit injection:
Total:          100 times.
Success:        100 times 100%.
        Exit:   7 times 7%.
        Signal: 93 times 93%.
        Sigalrm:        0 times 0%.
        Others: 0 times 0%.
Fail:           0 times 0%.
```

Figure 12 Fault injection results of parameters of two bits flip

Fault injection results on all types of bit flip of four types of system calls are shown in Table 4 to Table 7:

TABLE 4
FAULT INJECTION RESULTS OF FILE OPERATION SYSTEM CALLS

	1 bit inversion	2 bits inversion	32 bits inversion	1 bit set zero	2 bits set zero	32 bits set zero	1 bit set one	2 bits set one	32 bits set one	Mask
Exit	13	7	13	36	34	31	42	18	17	17
Abort	81	93	87	64	64	68	57	87	82	82
Alarm	6	0	0	0	2	1	1	1	1	1

TABLE 5
FAULT INJECTION RESULTS OF DISK READ AND WRITE SYSTEM CALLS

	1 bit inversion	2 bits inversion	32 bits inversion	1 bit set zero	2 bits set zero	32 bits set zero	1 bit set one	2 bits set one	32 bits set one	Mask
Exit	64	70	75	67	81	67	62	77	70	57
Abort	34	27	25	32	18	32	37	22	30	41
Alarm	2	3	0	1	1	1	1	1	0	2

TABLE 6
FAULT INJECTION RESULTS OF PROCESS CONTROL SYSTEM CALLS

	1 bit inversion	2 bits inversion	32 bits inversion	1 bit set zero	2 bits set zero	32 bits set zero	1 bit set one	2 bits set one	32 bits set one	Mask
Exit	34	6	0	100	100	100	20	2	0	100
Abort	13	34	25	0	0	0	28	35	29	0
Alarm	53	60	75	0	0	0	52	63	71	0

TABLE 7
FAULT INJECTION RESULTS OF SYSTEM SIGNAL SYSTEM CALLS

	1 bit inversion	2 bits inversion	32 bits inversion	1 bit set zero	2 bits set zero	32 bits set zero	1 bit set one	2 bits set one	32 bits set one	Mask
Exit	0	0	0	0	0	0	0	0	0	0
Abort	51	52	44	40	46	52	44	40	53	46
Alarm	49	48	56	60	54	48	56	60	47	54

The traditional fault injection method is to use ptrace to inject faults into registers and memory to simulate hardware failures. Table 8 is the fault injection results of the traditional fault injection method:

TABLE 8
FAULT INJECTION RESULTS OF THE TRADITIONAL METHOD

	IP 1 bit flip	Status register 1 bit flip	General register 1 bit flip	Memory(code/data segment) flip
Exit	15	12	74	100
Abort	81	0	26	0
Alarm	4	88	0	0

From the above results, we can see, the traditional fault injection tool for evaluating the robustness of the system has significant limitations, such as memory fault injection, judging from the robustness of the system are all normal exits and returns an error code. Using the method of abnormal parameters fault injection to the interface of system calls proposed in this paper compared with the traditional fault injection, can effectively lead to failure of the system robustness, and different types of system functionality can be classified to evaluate ,which help to assess robustness.

Calculate the system failure rate of this workload:

1) Calculate the average system failure rate after fault injection to the file operation system calls, disk read and write system calls, the process-related system calls and signal-related system calls under this workload: were 76.5%, 29.8% , 16.4% and 46.8% respectively.
2) Under normal circumstances of the workload, count various types of system calls used, results are as follows: system calls related to file operations are 320 times; system calls related to disk read and write are 410 times; system calls related to process control are 155 times; and system calls related to system signals are 747 times.
3) According to the proportion of various types of system calls, calculate the weights respectively: 0.20, 0.25, 0.10 and 0.45.
4) Calculate the system failure rate under this load:

$$F=\sum_{i=1}^{N} w_i \frac{f_i}{t_i}$$
$$=0.20*0.765+0.25*0.298+0.10*0.164+0.45*0.468$$
$$=0.153+0.0745+0.0164+0.2106$$
$$=0.4545$$

That is the system failure rate under this load is 0.4545.

D. Comparison and Analysis of Different Levels of System Robustness Test Results

1. Robustness comparison and analysis of API layer and DPI layer

Shown in Figure 13, the failure rate caused by DPI fault injection is greater than API, because the protection for functions of system kernel state decreases compared to the application functions [14,15], and therefore the robustness problems detected increase.

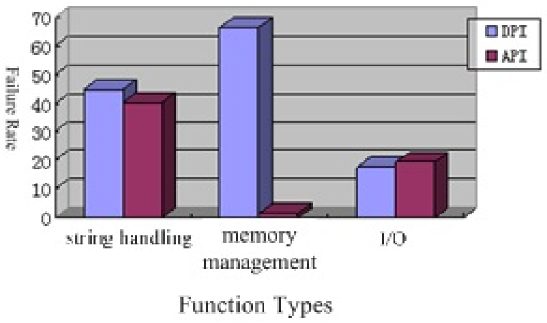


Figure 13 Comparison of DPI-API failure rate

In the API fault injection experiments, the case of system crash does not occur, and in the DPI fault injection experiments, five functions lead to system crash, because the kernel stack fault. Because fault injection to the kernel function can trigger a kernel state of failure, the seriousness of the failure sometimes is greater than the failure caused by the user state.

2. Robustness test results comparison and analysis of static function call and dynamic load

The robustness failure generated by fault injection to four different types of system call functions and the corresponding API function calls are shown in Figure 14:

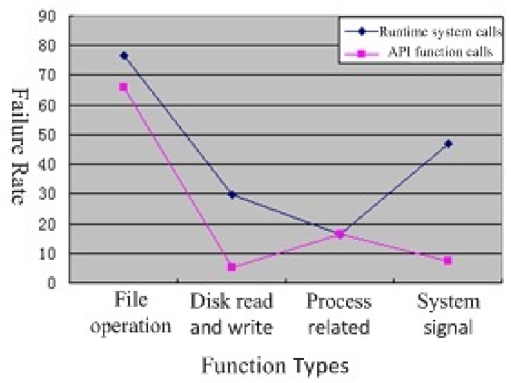


Figure 14 System failure rate comparison for run-time system call and static API functions after fault injection

Visibly, the probability of system failure caused by dynamic fault load is mostly greater than system failure caused by fault injection to the single interface. Especially for fault injection to the system calls associated with system signals in the load, the system failure probability is much larger than the corresponding single API call. There are two reasons:

1) System call interface is the kernel mode function, system failures injecting abnormal parameters in kernel mode are more than in user mode.
2) The spread of the fault caused by abnormal parameters of the function interface in the application will further lead to system failure, and which is closely related to the robustness of the application itself.

V. Conclusion

By comparing the classic robustness testing tools, this paper proposed the multi-level robustness testing strategy based on abnormal parameters for the architecture of Linux operating system, using the consistent fault injection method to inject faults to dynamic and static, user mode and kernel mode, to test the system robustness of the programming interface of user mode and kernel mode and the system robustness of dynamic load. The integrated fault injection platform implemented multi-level fault injection based on abnormal parameters and the incremental development of robustness testing tools. Using the integrated fault injection platform, test robustness of different levels for different versions of Linux systems, compare and analyze the relationship of the system failure rate between the robustness of static interface and dynamic load running. As robustness test results are generated from the consistent fault injection strategy, the test results of different levels have good comparability.

Due to the protection mechanism for system calls of high version of the kernel different, fault injection on DPI layer lacks portability, currently only implemented fault injection in the kernel of linux2.4. The fault injection strategy on the application load also requires further improvement, for a fuller evaluation of the system's robustness.

Acknowledgements

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