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CERTIFICATE

This is certify that the Seminar entitled

"Fault Tolerant Microkernel Extension with AI assisted System Calls"

submitted by

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This is to certify that **Sanchit Kumbhar 26** has successfully submitted Seminar entitled **"Fault Tolerant Microkernel Extension with AI assisted System Calls"** under the guidance of **Prof. B.R. Devhare** in the Academic Year 2025-26 at Computer Department of Trinity Academy of Engineering, under the Savitribai Phule Pune University. This Seminar work is duly completed.

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Sanchit Kumbhar

ABSTRACT

The increasing complexity and reliability demands of modern computing systems have highlighted the need for fault-tolerant and intelligent operating system architectures. This project, **"Fault-Tolerant Microkernel Extension with AI"**, aims to design and implement a robust microkernel architecture capable of autonomously detecting, isolating, and recovering from system faults with the assistance of artificial intelligence (AI) mechanisms. The proposed system enhances the traditional microkernel by integrating an AI-based fault prediction and adaptive recovery module that continuously monitors system calls, process states, and inter-process communication to identify anomalies in real time. Upon detection of potential faults, the AI module predicts failure points and triggers corrective actions such as process migration, service restart, or module isolation—without compromising the stability of the overall system. The microkernel structure ensures minimal performance overhead while maintaining system modularity, security, and resilience. Furthermore, the framework incorporates reinforcement learning techniques to optimize recovery decisions over time, improving the overall reliability and self-healing capabilities of the operating system. The results of this research demonstrate that integrating AI-driven fault management into microkernel architectures significantly reduces downtime and enhances system reliability, making it suitable for critical applications such as embedded systems, autonomous vehicles, and cloud infrastructure.

Keywords: *Fault Tolerance, Microkernel, Artificial Intelligence, Predictive Fault Detection, Reinforcement Learning, Process Recovery, System Reliability, Self-Healing Systems.*

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1 About Topic

1.1 Title

Fault Tolerant Microkernel Extension with AI assisted System Calls

1.2 Domain

System Programming and Machine Learning

1.3 Aim

To develop a AI based microkernel which could help the operating system to work much more effieciently by understanding the predictions made by the AI microkernel that what all faults may occur by analyzing the user's current activity.

1.4 Objective

- To enhance the reliability and fault tolerance of the microkernel architecture.
- To integrate AI-assisted mechanisms for intelligent system call management.
- To enable real-time fault detection, prediction, and recovery using machine learning techniques.
- To minimize system downtime and improve overall operating system stability.
- To maintain the modularity, security, and performance benefits of the microkernel design.

1.5 Problem Statement

Traditional microkernel architectures face challenges in maintaining system stability during faults or unexpected failures. Existing fault-handling mechanisms are static and lack intelligent adaptability. There is a need for a dynamic approach that can predict and recover from faults in real time. This project aims to integrate AI-assisted system calls to enhance fault tolerance and overall system reliability.

2 Introduction

The Fault Tolerant Microkernel Extension with AI Assisted System Calls integrates artificial intelligence into microkernel architecture to enhance system reliability and adaptability. In this approach, system calls are monitored and analyzed using AI models that predict potential faults or performance degradation. When an anomaly is detected, the AI dynamically adjusts or reroutes system operations to maintain stability and prevent system crashes. This intelligent fault management ensures minimal downtime, improved efficiency, and a resilient operating environment capable of self-healing in real time.

2.1 Need:

- To overcome the limitations of traditional microkernels that lack dynamic fault recovery mechanisms.
- To ensure uninterrupted system performance and minimize downtime during faults or failures.
- Data-Driven Insights: Current models may lack the granularity needed for precise assessments, necessitating improved modeling techniques that leverage advanced data analytics.
- To introduce AI-assisted decision-making for intelligent system call management and fault prediction. develop a self-healing architecture capable of adapting to unexpected system anomalies in real time.
- To enhance the overall reliability, stability, and resilience of the operating system.

2.2 Motivation:

- Modern operating systems demand high reliability and continuous uptime, even under fault conditions.
- The growing integration of AI in system-level design inspires the use of intelligent automation for fault detection and correction. fault-handling mechanisms in microkernels are limited to static recovery methods, leading to possible system crashes.
- Developing an AI-assisted microkernel encourages innovation in building adaptive, self-healing, and efficient OS architectures.
- This project is motivated by the need to create smarter, more resilient computing systems capable of learning from failures and improving over time.
- Traditional fault-handling mechanisms in microkernels are limited to static recovery methods, leading to possible system crashes.

2.3 Basic Concept

- Fault Detection: Monitoring system behavior and identifying anomalies or potential failures in real time within the microkernel environment.
- AI Assisted System Calls: Employing artificial intelligence to analyze system call patterns, predict faults, and make intelligent scheduling or rerouting decisions.
- Dynamic Fault Recovery: Automatically initiating recovery mechanisms such as task migration or service restart to maintain continuous system operation.
- Resource Optimization: Using AI models to manage CPU, memory, and I/O resources efficiently, ensuring balanced system performance under varying workloads.
- Learning and Adaptation: Continuously updating the AI model based on new fault data, enabling the system to become more resilient and adaptive over time.

3 Literature Survey

3.1 A Literature Survey on Operating System Architectures and Reliability

Operating systems are a foundational component of modern computing, and users expect them to function flawlessly. However, a significant body of research suggests that many common failures stem from a system's fundamental design. The traditional approach, the monolithic kernel, has been widely adopted but contains inherent structural properties that undermine reliability. In response, researchers have explored a design spectrum moving functionality out of the kernel, leading to single-server and multiserver microkernel-based designs, each with different trade-offs in reliability, fault isolation, and performance.

The most common OS structure is the monolithic kernel, where all core services—such as process management, file systems, and device drivers—are bundled into a single program running at the highest privilege level. Examples include "Vanilla Linux" and "Mac OS X". While this design can be performant, it presents significant reliability challenges. Its primary drawback is a lack of fault isolation; since all components run in the same address space, "any bug can potentially trash the entire system". Given that these kernels contain millions of lines of code, they are "likely to contain many bugs". Perhaps the most significant issue is the inclusion of device drivers, which empirical studies have shown are responsible for 70 percent to 85 percent of all operating system crashes.

In response to these problems, researchers explored microkernels, which aim to reduce the kernel to the smallest possible size, ideally providing only minimal mechanisms for inter-process communication (IPC) and scheduling. Other traditional OS services are pushed into user-mode processes, often called "servers". A common variant is the single-server system, which features a reduced kernel but runs "a large fraction of the operating system as a single, monolithic user-mode server". Examples include Mach-UX, which ran BSD UNIX on the Mach 3 microkernel , and Perseus, which ran Linux on the L4 microkernel. However, this architecture "adds little over monolithic systems" in terms of reliability. Because the bulk of the OS functionality still resides in one program, it remains a single point of failure.

The multiserver architecture takes this concept to its logical conclusion. Here, the operating system environment is "formed by a set of cooperating servers", with functionality extremely decomposed. Components like device drivers and file systems all run as "separate, user-mode modules". Early examples include MINIX, which still ran drivers in the kernel , and the abandoned SawMill Linux prototype. The commercial success of proprietary multiserver systems like QNX and Symbian OS, however, demonstrates the viability of the approach. This architecture is explicitly designed for reliability, providing true fault isolation and allowing for the principle of least authority to be applied, tightly controlling the power of each component. A key goal is the potential for self-healing, such as automatically replacing a crashed driver "transparent to applications and without user intervention".

Despite these clear benefits, multiserver architectures were "criticized for decades because of alleged performance problems". This reputation stems from early systems like BSD UNIX on Mach, which was "well over 50 percent slower" than its monolithic version , leading many to abandon the approach. However, more recent research has challenged this, with systems like L4Linux showing a performance loss of only about 5 percent and user-mode drivers performing within 7 percent of kernel-mode drivers. This suggests "the time has come to reconsider the choices that were made in common operating system design". The literature thus shows a clear progression from brittle monolithic kernels to more modular designs. While single-server systems failed to solve the "single point of failure" problem, the multi-

server architecture offers the most promising solution. The primary research challenge, addressed by the MINIX 3 paper, has been to synthesize these components into a complete, self-healing system capable of automatically surviving component failures ”transparent to applications and without user intervention” [11].

3.2 Fault Isolation for Device Drivers

Despite recent advances, commodity operating systems continue to fail to meet public demand for dependability. Studies indicate that unplanned downtime is primarily caused by faulty system software. Even well-written software contains faults, with estimates ranging from one fault per thousand lines of code (KLOC) using the best techniques to six faults/KLOC in general. Post-release data from projects with strict testing, like FreeBSD, confirms this with 3.35 faults/KLOC. Research has now established that extensions, particularly device drivers, are responsible for the majority of OS crashes. Drivers can comprise up to two-thirds of the OS code base, are often provided by untrusted third parties, and have an error rate 3-7 times higher than other code. Analysis of Windows XP crash dumps, for example, attributed 65-83

The root cause of this unreliability is the close integration of these untrusted extensions with the core kernel. This design violates the principle of least authority by granting excessive power to components that are likely to be buggy. A malfunctioning driver can overwrite critical kernel data structures, and memory corruption has been identified as one of the main causes of OS crashes. This problem is not feasible to fix through manual debugging, as configurations are constantly changing and the code base is rapidly expanding. The Linux 2.6 kernel, for instance, grew by 49.2

One major area of research involves running untrusted drivers inside the OS kernel but using wrapping and interposition techniques for safety. Nooks, for example, combines in-kernel wrapping with hardware-enforced protection domains to trap common faults and allow for recovery. Similarly, SafeDrive uses wrappers to enforce type-safety constraints and system invariants for drivers written in C. Another in-kernel technique is Software Fault Isolation (SFI), used in systems like VINO, which instruments driver binaries and uses sandboxing to prevent them from making memory references outside their logical protection domain. XFI builds on this by combining static verification with run-time guards to protect memory access and system state integrity.

A second approach uses virtualization to run services in separate, hardware-enforced protection domains , using technologies like VMware or Xen. However, simply running an entire OS in a single virtual machine is not sufficient, as a driver fault can still propagate and crash the entire guest OS. A more multiserver-like approach is needed, such as running each driver in a dedicated, paravirtualized OS within its own VM. The drawback to this method is that it can break strict VM isolation by introducing new, ad-hoc communication channels between the driver VMs and the client OS VM.

A third body of research focuses on language-based protection and formal verification. Systems like Singularity combine type-safe languages with protocol verification and ”seal” processes after loading to improve dependability. The seL4 project takes this further by aiming to create a formally verified microkernel, mapping its design to a provably correct implementation. Other tools in this space include Devil, an Interface Definition Language (IDL) for hardware programming that enables consistency checking , and Dingo, which simplifies driver-OS interaction by reducing concurrency and formalizing protocols.

Finally, a fourth approach, employed by multiserver systems like MINIX 3, is to encapsulate untrusted drivers in their own user-mode processes. This concept has been explored in systems like Mach

, L4Linux (which runs drivers in a paravirtualized server) , and NIZZA (which supports safe reuse of legacy extensions). This approach has entered the mainstream, with commodity systems like Linux and Windows now also using user-mode drivers. However, the provided paper notes that these implementations may not strictly adhere to the principle of least authority, which is the key to an truly dependable design.

This research has been made more practical by advances in hardware and a shift in priorities. Older PC hardware had shortcomings that made true isolation difficult, such as a lack of protection against unauthorized Direct Memory Access (DMA) and inter-driver dependencies caused by shared, level-triggered IRQ lines. Modern hardware has mitigated these issues with the introduction of IOMMUs, which provide memory protection for device-visible addresses , and the PCI-Express (PCI-E) bus, which uses a point-to-point design and message-signaled interrupts. Furthermore, as performance has increased, most end-users are now willing to sacrifice some performance for improved dependability. Independent studies have demonstrated that the overhead incurred by modular, microkernel-based designs can be limited to 5-10 percent, making the trade-off for a more reliable system increasingly practical. [5].

3.3 Dealing with Driver Failures in the Storage Stack

Operating systems are expected to function flawlessly, but contemporary commodity operating systems frequently fail. This gap between expectation and reality stems largely from faulty system software , and a strong consensus in the research community identifies device drivers as the primary source of this unreliability. Drivers represent a unique and massive threat. They comprise a significant and growing portion of the OS code base, in some cases up to two-thirds. This code, often provided by untrusted third parties, is notoriously buggy, with studies showing an error rate 3 to 7 times higher than other OS code. The consequences are severe: empirical analysis of crash dumps from systems like Windows XP has attributed 65-85

The root cause of this vulnerability is the fundamental monolithic design that underlies most common systems. This architecture integrates untrusted device drivers directly into the trusted core kernel , where they run with the highest privilege level. This design ”violates the principle of least authority” and provides ”no protection barriers enforced between the components”. As a consequence, a single malfunctioning driver can ”potentially trash the entire system” by corrupting kernel data structures. This makes memory corruption one of the main causes of OS crashes. From a high-level perspective, a monolithic kernel, such as that used by Linux , is ”unstructured” and provides no fault isolation.

In response to these reliability challenges, researchers have explored a spectrum of alternative OS architectures. A common evolutionary step was the development of microkernels, which led to the single-server system. This design, seen in early systems like Mach-UX , runs a large fraction of the OS as a single, monolithic user-mode server on top of a reduced kernel. However, in terms of reliability, this architecture ”adds little over monolithic systems”. Because the bulk of the OS functionality still resides in one program, it merely moves the ”single point of failure” from kernel space to user space, with the only ”gain” being a ”faster reboot”.

The logical conclusion of this design trend is the multiserver operating system. This architecture, ”explores an extreme in the design space” by running the entire operating system as ”a collection of independent, tightly restricted, user-mode processes” on top of a minimal kernel. This design, used by systems like MINIX 3 , QNX , and prototyped in SawMill Linux , is explicitly ”designed for reliability”. It provides proper fault isolation by moving most code to unprivileged processes, thereby ”limit[ing] the

damage bugs can do". This enables the creation of a self-healing system that can "automatically recover from failures in critical modules". While early multiserver systems built on microkernels like Mach were "abandoned for performance reasons" and heavily criticized , the literature suggests "the time has come to reconsider" these designs. Modern research has shown that the performance overhead is no longer a blocking issue, with systems like L4Linux and user-level drivers demonstrating overheads as low as 5-10

The multiserver user-mode driver model is one of several approaches to driver isolation found in the literature. One category of techniques involves adding safety to existing monolithic kernels via wrapping and interposition. Nooks, for example, combines in-kernel wrapping with hardware-enforced protection domains to trap faults. SafeDrive uses wrappers to enforce type-safety constraints for C-based drivers, while Software Fault Isolation (SFI), used in systems like VINO , instruments driver binaries to "prevent memory references outside their logical protection domain". A second approach is virtualization , using VMMs like VMware or Xen. However, "running the entire OS in one virtual machine is not enough" to solve the driver problem; a multiserver-like approach is required, where each driver runs in a dedicated paravirtualized OS within its own VM.

A third category is language-based protection and formal verification. This includes systems like Singularity , which combines type-safe languages with protocol verification, and the seL4 project , which aims for a "formally verified microkernel". Other tools, such as the Devil and Dingo projects, focus on formalizing protocols to simplify driver-OS interaction. However, simply isolating a fault and restarting the driver is not a complete recovery strategy for all components. For networking, this "transparent recovery" is possible because the TCP protocol provides its own end-to-end integrity and can simply retransmit garbled or lost packets. The storage stack, in contrast, is a far more difficult problem because it "lack[s]... end-to-end integrity".

A simple restart of a block-device driver cannot detect or prevent silent data corruption. A buggy driver might "not crash but return... bogus data" , write data to the "wrong position on disk" , or simply "not write the data" at all but still report success. The literature on storage integrity exists at several levels. At the hardware level, modern standards like SCSI Data Integrity Field (SCSI DIF) and SATA External Path Protection (SATA EPP) provide integrity metadata. However, this approach "requires modern hardware" and metadata-aware drivers, and thus "does also work with legacy hardware". At the file-system level, several systems provide their own protection. PFS , Ext4 , and ZFS all implement some form of checksumming. ZFS, for instance, stores checksums in parent block pointers to provide fault isolation. While effective, the "downside... is that developing a new file system requires a huge effort" and these solutions "cannot be generalized to existing systems".

This has led to research on intermediate layers. Stackable file systems operate at the file (vnode) level, and projects like IRON File Systems have proposed grouping reliability policies. The most relevant related work is IOShepherd, a layer below the file system that enforces integrity. Its primary drawback, however, is that "using IOShepherd to enforce reliability requires making the file system 'Shepherd-Aware'". This involves changes to the file system's "consistency management routines, layout engine, disk scheduler and buffer cache". This highlights a research gap for a transparent filter-driver framework. A key differentiator for the multiserver approach is that while a driver failure in a monolithic system would "be fatal" , a multiserver OS like MINIX 3 can "compartmentalize" the fault and provide a foundation for true recovery, such as "replacing drivers on the fly". [2].

3.4 Safe and Automatic Live Update for Operating Systems

A pressing demand for 24/7 operation in critical infrastructure, such as e-banking servers and power plants, has made the traditional ”patch-install-reboot” cycle an unacceptable source of downtime. Modern operating systems evolve rapidly, with studies on the Linux kernel showing hundreds of new versions and a growth of millions of lines of code over a decade. This creates a constant stream of updates for new features, bug fixes, and security vulnerabilities that must be deployed without stopping running services. The clear solution to this problem is live update—the ability to upgrade a running system on the fly with no service interruption. However, a review of the literature shows that existing solutions are not yet ”practical and trustworthy”. Most solutions explicitly target only ”small security patches” and cannot effectively handle more complex updates, such as upgrading between major operating system versions. The literature reveals that existing solutions scale poorly with both the complexity of an update and the number of updates applied. These limitations stem from a lack of system support for two fundamental challenges: defining a safe update state and performing a reliable state transfer.

The first great challenge discussed in the literature is determining a safe update state. The validity of applying a live update in an arbitrary system state has been shown to be undecidable in the general case, meaning that system support and manual intervention are ”needed”. Much of the prior work, including the commercially successful Ksplice system, has relied on the notion of function quiescence. This principle allows an update to proceed only when the functions being changed are not on the call stack of any active thread. However, this is ”a weak requirement for a safe update state”. As an example inspired by the Linux kernel’s fork implementation demonstrates, an update can be unsafe even if the changed functions are quiescent. If a call is moved from one function to another, an unchanged calling function could execute the old version of the first function and the new version of the second, resulting in an incorrect execution state (e.g., calling a function twice instead of once). To address this, the literature has proposed ”pre-annotated transactions” or static analysis , but these strategies ”do not easily scale” and ”expose the programmer to the significant effort of manually verifying update correctness”.

The second, and arguably greater, challenge is state transfer: migrating the runtime state from the old version to the new one. The literature has focused on three dominant approaches for handling data type transformations in C: type wrapping , object replacement , and shadow data structures. Type wrapping performs in-place transformations, object replacement dynamically loads new objects and copies the state, and shadow data structures preserve old objects while loading only new fields. While some research has automated the generation of type transformers , ”none of the existing live update solutions for C provides automated support for transforming pointers and reallocating dynamic objects”. This failure to ”properly handle pointers into updated objects can introduce several problems, ranging from subtle logical errors to security vulnerabilities”. For example, type wrapping can lead to ”type-unsafe memory reads/writes for stale interior pointers,” which is ”similar to a typical dangling pointer vulnerability”. Object replacement can introduce ”misplaced reads” from stale base pointers that erroneously read data from the old object instead of the new one. Finally, shadow data structures can lead to ”uninitialized read vulnerabilities” when non-updated code accesses new fields as raw data. Prior solutions have proposed static analysis to identify these cases , but this approach ”scales poorly” and may simply ”disallow updates as long as there are some live pointers” , forcing ”extensive manual effort”.

A survey of specific implementations reveals these limitations in practice. In the OS kernel space, solutions have primarily targeted Linux. Ksplice was a ”important step forward” that used binary rewriting and shadow data structures but was evaluated on small security patches, not complex updates. It

relies on function quiescence and ”provides no support for automated state transfer, state checking, or hot rollback”. Other Linux-based solutions, DynaMOS and LUCOS , ”advocate running the old and the new version in parallel” , a strategy that ”leads to a highly unpredictable update process”. In both systems, the critical task of state transfer is ”delegated entirely to the programmer”. A parallel body of literature has targeted user-space C programs, using techniques like compiler-based transformations (e.g., Ginseng, Stump) or binary rewriting (e.g., OPUS, POLUS). These solutions ”offer no support to specify safe update states on a per-update basis, do not attempt to fully automate state transfer or state checking, and fail to ensure a transactional... update process”.

Finally, all these in-place solutions share a common, critical flaw: they are not stable. A stable update process is one where the system’s behavior does not degrade after multiple updates. This property is ”crucial for realistic long-term deployment”. The ”in-place strategy” used by most of the C-based and kernel-based literature ”repeatedly violate[s] the stability assumption”. By ”gluing code and data changes directly into the running version” , these systems introduce ”memory leakage” from dead code and data that cannot be reclaimed, and ”poorer spatial locality” due to address space fragmentation. Prior work on server applications has reported as much as a 40 percent memory footprint increase and 29 percent performance overhead after only 10 updates. Systems that use binary rewriting also introduce a number of ”trampolines” that grows linearly with the number of updates, adding further overhead. Even alternative architectures, like the object-oriented K42 , which solve the stability problem, introduce new issues, such as a quiescence model that can lead to ”unrecoverable deadlocks” and still provide ”no support for automated state transfer”. Thus, the literature demonstrates a clear need for a new approach that is stable, safe, and automated. [7].

3.5 Back to the Future: Fault-tolerant Live Update with Time-traveling State Transfer

The modern software landscape has undergone a major paradigm shift, moving from periodic releases like ”Patch Tuesday” to continuous development models with release cycles measured in days or even hours. This acceleration creates a constant stream of updates for new features, security fixes, and performance enhancements. This trend is in direct conflict with a ”growing reliance on nonstop software operations” for mission-critical services. The standard ”halt-update-restart” cycle is no longer acceptable. To mitigate this, system administrators often rely on ”rolling upgrades,” updating one node at a time in a replicated system. However, the literature identifies significant shortcomings with this approach: it requires redundant hardware, it typically ”cannot normally preserve program state across versions,” and it introduces significant update latency, which creates high exposure to ”mixed-version races”. These mixed-version bugs can lead to catastrophic failures, such as one ”of the biggest computer errors in banking history” where a single-line update caused millions in erroneous deductions.

Live update, the ability to update software on the fly ”with no service interruption,” is a ”promising solution” to this problem that does not suffer from the limitations of rolling upgrades. However, despite years of research, live update systems are ”still far from reaching widespread adoption”. The literature suggests this is ”largely motivated by the lack of tools to automate and validate the live update process”. A significant gap exists in building ”trustworthy update systems” that are as usable and reliable as regular, offline updates. Administrators are often reluctant to install even regular updates, making a large gap in reliability a non-starter for adoption.

The ”major obstacle” to this adoption, which has been ”repeatedly recognized as a challenging and error-prone task” in the literature, is state transfer (ST). State transfer is the process of ”initializing the

state of a new version from the old one". The problem, first rigorously defined by Gupta, has two main formulations: the live initialization of data structures, which may involve "structural or semantic data transformations" , and the more complex transfer of the full execution state, including "remapping the call stack and the instruction pointer". This task is so difficult that existing live update tools "largely delegate [it] to the programmer," despite the "great effort involved".

The commercial success of Ksplice serves as a prime example of this problem. Ksplice, which has been "deployed on over 100,000 production servers," is "explicitly tailored to small security patches that hardly require any state changes at all". This success demonstrates that while the concept of live update is valuable, the field has sidestepped the core challenge of complex state transfer. A simple security patch, such as a fix for an information disclosure vulnerability in the Linux kernel's md driver, often "introduces simple code changes that have no direct impact on the program state". For such an update, "no state transformations are required," and an in-place tool like Ksplice can simply redirect function calls to the new code. However, a more typical update—one that "introduces a number of type changes affecting a global struct variable"—"significantly changes the in-memory representation" of the program's state. In this common scenario, "state transfer... is necessary to transform the existing program state into a state compatible with the new version". Failure to do so "would leave the new version in an invalid state".

The literature qualitatively describes this task as involving "tedious implementation of the transfer code" and "tedious engineering efforts". Quantitative analysis of user-level live update tools for C programs, such as Ginseng, STUMP, and Kitsune, confirms this. This analysis shows that the manual effort required for state transfer "increasingly (and heavily) dominates" as more updates are applied. Furthermore, this "LOC-based metric underestimates the real ST effort," which involves an "atypical and error-prone programming model".

A survey of specific live update systems reveals a consistent pattern. Kernel-level solutions for Linux, such as LUCOS, DynaMOS, and Ksplice, all use an "in-place update model," "gluing" changes directly into the running version. They use techniques like binary rewriting for code changes and shadow or parallel data structures for data. Critically, "Most solutions delegate ST entirely to the programmer". The same is true for user-space C solutions like OPUS, POLUS, and Ginseng, which use methods like compiler-based instrumentation or stack reconstruction. These systems either delegate state transfer or "generate only basic type transformers," failing to "fully automate ST—pointer transfer, in particular". This in-place model also introduces long-term "address space fragmentation" and "run-time performance overhead". Even alternative models, such as process-level live updates or Kitsune's shared-library approach , have "delegate[d] the ST burden entirely to the programmer" or failed to "automate pointer transfer without user effort".

While state transfer is one major gap, the literature reveals a second: the lack of robust validation. "Surprisingly, there has been limited focus on automating and validating generic live updates". The "typical strategy" for validation, when it is considered, is "update timing-centric". This "extensive focus on live update timing" is concerned with "validating the correctness of an update in all the possible update timings" , ensuring a test suite completes correctly regardless of when the update is applied. This has led to research on quiescence (waiting for code to be inactive) and "representation consistency". Recent work has even suggested that the field "may have been overly concerned with update timing," noting that "a few predetermined update points" are often sufficient.

This preoccupation with timing has meant that "Much less effort has been dedicated to automating and validating state transfer" itself. Existing live update testing tools "are only suitable for offline testing,"

”add no fault-tolerant capabilities to the update process,” and ”fail to validate the entirety of the program state”. Static analysis in systems like OPUS and Ginseng is ”only useful to disallow particular classes of (unsupported) live updates,” not to validate the correctness of the transfer. This leaves a critical gap in the literature: a solution that not only automates the ”challenging and error-prone task” of state transfer but also provides a fault-tolerant way to validate the ”full integrity of the final state” during an online update. [1].

3.6 A Literature Survey on Fault Injection and Failure Characterization

Fault injection has established itself as the de facto standard technique for system dependability benchmarking. Its versatility and relatively low cost have allowed researchers to assess the dependability of a wide range of systems, including distributed and local user programs, operating systems, file caches, and device drivers. A significant body of prior work in this area has focused on the development of general-purpose fault injection tools and methodologies. These studies cover a variety of implementation strategies, with a common theme being the introduction of program mutations that mimic realistic software or hardware faults. These mutations have been applied at different stages, including the source code level, the binary level, or, more recently, at the intermediate code level using compiler frameworks. An alternative strategy is to introduce these program mutations at runtime, using mechanisms such as software and hardware traps or library interposition.

Until recently, however, there has been ”little attempt to investigate the general properties of fault injection and its impact on the running system”. Many studies that do explore these properties have been primarily concerned with the efficiency and realism of the injection process, rather than the full spectrum of behaviors that result. This includes research focused on what to inject, where to inject, and how to inject faults to ensure they are realistic and representative of actual software faults. Other studies have investigated methods to improve fault activation guarantees, for example by injecting faults into ”hot code spots” identified through program profiling. The goal of this work is often to ”eliminate invalid runs with no faults activated” and thereby ”improve the efficiency of large-scale fault injection experiments”. Similarly, efficient fault exploration strategies have been developed that ”rely on domain-specific heuristics to drastically reduce the number of fault injection runs to the interesting cases”.

While these studies are valuable for refining the fault injection process itself, ”all these studies reveal little insight into its impact on the system behavior”. The research that has sought to analyze the impact of artificially injected faults has traditionally done so without attempting to fully characterize the system’s behavior, which has led to a critical blind spot: the impact of silent failures. ”Traditional characterization studies,” for instance, ”solely focus on fail-stop behavior” —such as program crashes—or other ”high-level properties directly exposed to the user view of the system”. Even more recent studies, which investigate how faults progressively propagate throughout a system, have limitations. The ”typical strategy” in this area is to ”rely on taint analysis techniques to identify all the corrupted portions of the internal system state”. While this method can expose some failures that do not result in an immediate fail-stop, this ”strategy cannot alone pinpoint behavioral changes that corrupt the external state of the system and eventually lead to subtle long-term failures”. Given that prior work has demonstrated that fault propagation often results in ”transient internal state corruption” , any research strategy that ”ignores behavioral changes and external state corruption” is likely to ”heavily underestimate the impact of silent failures”.

This gap in the fault injection literature is mirrored in bug characterization studies that analyze real-

world software faults. Most of these studies ”do not specifically consider silent failures”. Instead, their focus tends to be on fail-stop behavior, fault propagation, or the challenges of bug reproducibility. A ”notable exception” is the work by Fonseca et al. on concurrency bugs. This study introduced a concept of ”latent bugs,” which is described as being ”similar, in spirit, to our definition of silent failures”. This research is significant as it ”demonstrates the substantial presence of silent failures in real-world bug manifestations” and confirms that these failures are ”most often induced by corruption of external system state—persistent on-disk state, in particular”. However, this investigation was limited to the specific domain of concurrency bugs, required ”extensive manual analysis,” and was based on a ”relatively small sample size”. This highlights the need for a methodology that can deliver the ”more stable and general results” that a large-scale, ”automated analysis of fault injection results” could provide.

The methodology for such an automated analysis can draw inspiration from several related fields. The general approach of comparing faulty and fault-free execution runs is inspired by prior work that used ”state diffing techniques” , though these earlier efforts had a different purpose (evaluating fault-tolerance mechanisms) and scope (analyzing the internal system state, not its external behavior). The technique of ”system call-based behavior characterization” is inspired by ”anomalous system call detection” used in intrusion detection. An analysis framework can be ”simpler and more conservative” than these security tools because it ”compares semantically equivalent execution runs” rather than trying to model normalcy from scratch. This detection strategy is also conceptually related to N-variant systems, which compare runs to detect security attacks, and multi-version execution, which compares runs to perform online patch validation. Finally, a ”cross-execution system call matching strategy” can be inspired by ”mutable record-replay techniques”. However, because the goal is post-mortem analysis of completed runs rather than on-the-fly replay, this ”drastically simplifies” the matching strategy and ”need not rely on the sophisticated heuristics proposed in prior work”. [10].

3.7 Evaluating Distortion in Fault Injection Experiments

Despite decades of advances in software engineering, modern software systems remain plagued by critical bugs. Several studies have shown that the number of bugs in a piece of software, even in mature systems, is ”roughly linear with the program size”. While formal methods have been proposed to address this, the effort required remains a significant barrier to widespread adoption. The ”heroic effort” required for formal verification, such as the 20 person-years spent on the 9,300 lines of code for the seL4 kernel, is not currently realistic for software systems that are hundreds or thousands of times larger. Furthermore, even formal specifications can contain their own bugs or rely on the correctness of other components, such as compilers and hardware. As a result, software bugs are a persistent reality, which means ”fault containment and recovery mechanisms still play a pivotal role in the design of highly reliable systems”.

To validate these critical fault-tolerance mechanisms, it is ”often necessary to evaluate the behavior of a system under faults”. In an ideal scenario, this validation would use real software faults, but ”identifying a sufficiently large number of real software faults is normally not an option”. Therefore, fault injection techniques have been developed as the standard alternative, allowing researchers to ”artificially inject faults and compare the run time behavior of the system during fault-free and faulty execution”. Fault injection is a ”popular technique” for dependability benchmarking, in large part because it is ”relatively inexpensive, scales efficiently to large and complex programs, and allows users to emulate special conditions not necessarily present in the original program code”.

The literature describes the application of fault injection across a wide variety of software classes.

It has been used to benchmark the dependability of components such as device drivers , file caches , entire operating systems , user programs , and large-scale distributed systems. The ”typical evaluation scenarios” for these experiments include ”analyzing the behavior of a system under faults” , ”conducting high-coverage testing experiments for existing error recovery code paths” , or evaluating the ”effectiveness and containment properties of fault-tolerance techniques”.

To conduct these evaluations, researchers have developed ”several possible fault models”. These models reflect different fault scenarios and ”serve a unique purpose in the reliability testing process”. Some fault injection strategies are designed to emulate simple ”hardware faults,” such as bit flips. Others focus on ”faults at the component interfaces,” such as simulating ”unexpected error conditions” at the library level or the system call level. A third, and particularly critical, category focuses on emulating the ”real-world software faults” that are ”introduced by programmers”. The ”injection techniques” used to implement these models are similarly varied. Some strategies rely on ”static program mutations,” which can be applied using ”compiler-based strategies” at the intermediate code level or directly at the binary level. Alternative ”run time strategies” can interrupt the program’s execution to inject a fault, using mechanisms like ”timers” or ”predetermined hardware or software traps”.

When selecting from these models and techniques, ”an important question prior work has sought to address is whether the model is representative” of the real-world fault scenario it is intended to simulate. This concept of ”representativity” is ”important for the validity and comparability of the final results”. A significant amount of this research has been ”devoted to emulating realistic software faults found in the field”. This includes studies that consider ”how accurately artificially injected fault types represent real-world fault types”. The G-SWFIT tool, for instance, is a notable example of a system that ”injects fault types based on real-world bugs found in existing software”.

Other studies in the literature have focused on the ”accuracy of the different injection strategies” themselves. This research compares the outcomes of different techniques, such as the work by Cotroneo et al. analyzing the ”accuracy problems of binary-level injection strategies when compared to source-level program mutations”. Similarly, Christmansson et al. have compared ”location-based injection strategies with timer-based approaches” , and Madeira et al. have investigated the ”general limitations” of fault injection when ”compared to real faults found in the field”. ”In another direction,” a body of work exemplified by Natella et al. has considered the problem of ”fault location representativeness”. This research argues that ”so-called residual faults” are the ”most representative of real-world bugs” because these are the faults that ”escape software testing” and are ultimately ”found in production systems in the field”.

However, this collective body of research, while valuable, has a significant limitation: it is ”solely focused on representativeness and accuracy of the input fault load”. That is, the literature has been overwhelmingly concerned with defining the intended fault model. In contrast, research on the fidelity of the output fault load—the set of faults that are actually activated during an experiment—”has received much less attention in the literature”. This distinction is critical, as the ”output fault load may differ considerably from the input fault load”.

While ”a number of prior approaches have considered the impact of code coverage on fault injection experiments” , their ”focus is limited to ensuring reasonable fault activation”. This paper argues that ”fault activation itself is a poor metric” for evaluating the quality of an experiment’s results. The paper introduces the concept of distortion to describe the difference between the input and output fault loads. This distortion, which can be ”biased towards particular fault types or locations,” means that the ”activated faults do not faithfully reflect the original fault model”. This new concept of ”fidelity” is ”much

more rigorous" than simple activation, as it is "able to capture the full dynamics of both the test program and the workload" —factors that the literature has largely failed to analyze. This gap is what the current paper aims to fill, by "providing a definition of fault injection fidelity" and "performing the first large-scale evaluation of fidelity" to "quantify the validity and comparability of fault injection results". [4].

3.8 Towards a Flexible, Lightweight Virtualization Alternative

The concept of virtualization in computer systems has been established for a long time, but it has only "gained widespread adoption... in the last fifteen years". Its primary uses are to "save on hardware and energy costs by consolidating multiple workloads onto a single system" and to "create host-independent environments for users and applications". In the modern computing landscape, the literature shows that "two virtualization approaches have established themselves as dominant: hardware-level and operating system-level (OS-level) virtualization". These two approaches are "fundamentally different in where they draw the virtualization boundary" , which is the "abstraction level at which the virtualized part of the system is separated from the virtualizing infrastructure". The placement of this boundary is the single most important factor, as it "determines important properties of the virtualization system".

The first dominant approach is hardware-level virtualization. This approach "places the virtualization boundary as low in the system stack as practically feasible" , specifically "at the machine hardware interface level". In this model, a host layer, known as a "virtual machine monitor or hypervisor" , provides its "domains" —which are called "virtual machines" —with a set of abstractions that "are either equal to a real machine or very close to it". These abstractions include "privileged CPU operations, memory page tables, virtual storage and network devices, etc.". The primary benefit of this low-level boundary, as documented in the literature, is "full freedom". It allows a "full software stack," including a complete operating system and its applications, "to run inside a domain with minimal or no changes". This provides "strong isolation" and is "generally thought of as more flexible".

Despite its flexibility, the literature identifies significant drawbacks to the hardware-level approach. The inclusion of a full OS in each domain "adds to the domain's footprint". More critically, it leads to systemic "duplication and missed opportunities for global optimization". This is because "several fundamental abstractions are common across OSes," such as "processes, storage caches, memory regions, etc.," and "reimplementing these in isolation" is inefficient. This problem is known in the field as the "semantic gap". Because the boundary is so low, "the host lacks necessary knowledge about the higher-level abstractions within the domains". For example, the host cannot effectively manage memory because it does not know which pages are free within the guest OS, leading to problems like "double paging". The literature is replete with "many ad-hoc techniques" designed to "work around this gap". These workarounds include techniques like "ballooning" to reclaim memory, "virtual machine introspection" to monitor the guest, and various methods for "enlightened page sharing" , "hypervisor exclusive cache[s]" , and "cross-layer hints" to reduce memory duplication.

At the "other end of the spectrum" is operating system-level virtualization, also known as containerization. In this approach, the "virtualization boundary" is placed "relatively high, at the operating system application interface level". The "operating system itself has been modified to be the virtualization host" , and the domains, or "containers" , "consist of application processes only". All "system functionality is in the OS". Each domain receives a "virtualized view of the OS resources," such as its own "file system hierarchy, process identifiers, network addresses, etc.". The primary advantages of this model are that it

is ”faster and more lightweight”. Because the OS ”doubles as the host, there is no redundancy between domains and resources can be optimized globally”. However, the literature also notes significant ”downsides” to merging the host and OS roles. First, it ”eliminates all the flexibility” of the hardware-level approach; domains ”have to make do with the abstractions offered by the OS”. Second, it ”removes an isolation boundary,” meaning that ”failures and security problems in the OS may now affect the entire system rather than a single domain”.

Given the trade-offs of these two dominant models, a body of research has emerged arguing that ”these two existing approaches are extremes in a continuum”. This perspective suggests that ”a wide range of choices” exists in a ”relatively unexplored yet promising middle ground”. A ”middle-ground approach” would feature a host layer that ”provides abstractions to its domains that are higher-level than those of hardware, and yet lower-level than those of OSes”. Each domain would then run a ”system layer” that uses these ”mid-level” abstractions to ”construct the desired interface for its applications”. This design has the ”potential to reduce the footprint of the domains while retaining much of their flexibility and isolation”. The one major ”compromise” this approach must make is ”the ability to run existing operating systems” unmodified, as they are not built for this new, mid-level boundary.

This ”middle ground” concept has been explored in several related research areas. For example, some proposals, such as Zoochory , have suggested a ”middle-ground split of the storage stack”. This proposal, however, ”focuses on virtualization-unrelated advantages” and specifically suggests the host interface ”be based on content-addressable storage (CAS)”. Other research has argued for an ”object storage model” as the mid-level abstraction, where the host provides an ”object store” and the domain’s system layer is free to ”implement the file system abstractions appropriate for its user applications”. This concept extends to memory, where a ”centralized page cache” in the host can ”avoid in-memory duplication of cached data between domains altogether” and ”can be CoW-mapped into domains”.

This exploration of a new virtualization boundary ”shows similarity to several microkernel-based projects”. The microkernel philosophy, which also decomposes traditional OS services, is a natural fit. For instance, the L4Linux project ”uses task and memory region abstractions to separate virtualized processes from a virtualized Linux kernel”. Other ”L4-based projects” in the literature ”combine microkernel features with virtualization” , although often ”without further changing the virtualization boundary”. The GNU Hurd OS has a ”subhurds” concept with ”long-term plans similar to ours”. Similarly, the Fluke microkernel ”shares several goals” with this approach, but its unique ”support for recursion” led to a different design where ”high-level abstractions” must be ”defined at the lowest level”. Other researchers, such as ”Roscoe et al” , have also argued ”in favor of revisiting the hardware-level virtualization boundary”. However, most such proposals ”generally keep the low-level boundary in order to support existing OSes”, thereby failing to escape the semantic gap. The ”middle ground” remains a largely unexplored design space that may ”combine several good properties of both” extremes. [3].

3.9 Battling Bad Bits with Checksums in the Loris Page Cache

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3.10 The Rise of Heterogeneous Architectures and the OS Gap

A major trend in hardware development is the move toward heterogeneous multicore architectures. These systems, exemplified by designs like the ARM big.LITTLE, NVIDIA Tegra-3, and the x86-compatible Xeon Phi, combine different types of cores on a single die . These cores typically share "a large subset of the instruction set architecture (ISA)" , allowing the same code to run on any core, but they possess different microarchitectures designed for different "optimal operation points". The literature broadly categorizes these into "big" and "little" cores, or "BOCs" (Big Out-of-Order Cores) and "SICs" (Simpler In-Order Cores). "Big" cores, such as those in the Intel Core i7 "Bloomfield," are complex, "out-of-order" (OoO) designs with "deep pipeline[s]" geared for "high single threaded throughput". In contrast, "little" cores, like those on the Knights Ferry or Xeon Phi, are "much simpler, in-order" designs, often with "shallow pipelines," that "cannot deliver performance equal to the big ones" but are far more numerous and power-efficient. The research community has "advocated such heterogeneity for many years". Seminal work by Kumar et al. "proposed single-ISA heterogeneous multi-core architectures" specifically for "processor power reduction" and to "improve performance of multithreaded workloads". This research demonstrated that "applications need a good mix of single-threaded performance and high throughput" and that, as a result, "heterogeneous platforms outperform homogeneous ones with the same die size". This has made heterogeneity "promising for the future". However, this body of research "was primarily on applications, leaving the operating system by the wayside". This is a "remarkable" omission, as the "operating system performs a significant amount of work on behalf of the applications".

The Scheduling Problem: Making Heterogeneity Work for Applications Given that the hardware platform is heterogeneous, the "operating system[] are key to leveraging" these platforms, and as a

result, ”the schedulers got the most attention” in the research community. The central challenge is that ”the execution of applications changes during different phases,” and the scheduler must ”make decisions where each application runs”. The literature has explored several strategies to solve this. Early work, such as that by Kumar et al., ”proposed a whole range of sampling heuristics that permute threads on cores to find the best assignment”. A more dynamic approach was proposed by Becchi et al., who developed ”a dynamic algorithm which constantly measures the IPC ratio of threads” and ”tries to run on the big cores those threads that would benefit the most”. However, this ”permuting the threads and sampling” creates its own ”overhead”. To address this, Koufaty et al. ”designed a scheduler which monitors execution of each thread on its current core only”. This lightweight approach ”uses existing low overhead performance monitoring counters to collect performance related data”. This data is then fed into ”a model which translates the performance statistics to the bias of each thread to a certain type of a core”. Most of these algorithms rely on a ”speed up factor,” or the ”ratio between how fast an application runs on a small and a big core”. Saez et al. later suggested that a ”more comprehensive utility factor” was needed to determine ”how effectively the whole mix of running application uses the machine”. To remove the guesswork and modeling from this process entirely, other research has ”proposed as hardware extensions” ”hardware monitoring and prediction engines” and ”performance impact estimators”. In this model, the ”hardware estimates the possible speed-up on its own and the scheduler can use this direct feedback”.

Beyond Applications: The Operating System on Asymmetric Cores While the aforementioned literature focuses heavily on scheduling applications, the research presented in this paper argues that the operating system itself has different needs. The ”main focus is on the system,” and ”system code differs from application code”. Unlike general-purpose applications, OS components ”are responsible for a small subset of all the system tasks” and therefore ”have little variance during their execution”. Furthermore, these components ”are not opaque for the system”; the ”system designer knows more about the system components,” which ”can help the scheduler by providing various hints”. For example, a component could ”signal when the recipient of its messages cannot keep up and thus may benefit from a faster core”. The scheduler’s goal for the OS is ”not to let the system finish as quickly as possible, but to deliver optimal service”. The literature that has explored the OS on heterogeneous cores has focused on two main areas. First, Mogul et al. ”proposed operating system friendly cores” with the primary goal of ”sav[ing] power”. This design proposes that ”the system should run on the optimized cores” and that ”the execution should transfer from the application cores to the system cores when necessary”. However, this ”migration is a bottleneck” that ”means that the cache locality is poor”. Strong et al. also worked on addressing this migration overhead. The second area of related work is exemplified by FlexSC, which ”aims to remove the overhead of switching between applications and the system by running each on different cores”. A multiserver OS design, like that of NewtOS, is ”more suitable for heterogeneous platforms” because it naturally avoids this migration bottleneck. Rather than migrating a thread, it ”moves execution only by sending a message to another core,” which ”benefits from cache locality of the code and data of the component running on the core”.

Case Study: High-Performance, Reliable Networking on Heterogeneous Systems A key challenge for alternative OS architectures, such as the reliable ”UNIX-like multiserver system” NewtOS, has been performance. Multiserver systems, which are ”composed of independent user space servers,” ”typically trade reliability for performance”. The ”communication and context switching to share the processor constitute a significant overhead”. Previous research on NewtOS, a ”high-performance derivative of MINIX 3,” showed ”that it is possible to mitigate this overhead by dedicating cores to system servers”.

This approach ”fixes both” of the ”key performance problems that plagued multiserver systems in the past”. With dedicated cores, ”system servers can run whenever needed from a warm cache” and communicate via ”asynchronous channels,” which are ”shared user space memory queues”. This architecture, designed for ”high reliability” (including ”dynamic updates without any downtime” and recovery from ”crashes of core OS components”), also enables high performance. This provides the context for applying heterogeneous research: if components run on dedicated cores, it becomes critical to know if they need ”big” cores or if ”little” cores will suffice. Other research in high-performance networking has also focused on user space. The ”Netmap” and ”OpenOnload” projects ”demonstrated high bandwidth networking in user space”. Netmap, for instance, showed ”that a 900 MHz core is good enough to transfer 10 Gbps of small packets”. However, these solutions differ from a multiserver OS in a critical way: ”both need a driver in a monolithic kernel”. This means ”there is still a chance that a bug in the driver can bring the whole system to a halt”. In contrast, the NewtOS design ”split[s] the stack into several components (TCP, UDP, IP, drivers...)” precisely ”to reduce the chance that an error in the stack may lead to a crash of the entire stack”. This body of literature, therefore, establishes the dual challenge: achieving the reliability of a component-based OS while matching the performance of less reliable user-space or monolithic systems.[9].

3.11 Safe and Automatic Live Update for Operating Systems

The paper begins its survey by establishing the difficulty of performing live updates safely, noting that the validity of an update in an arbitrary state is generally undecidable. It critiques existing approaches that define a safe update state using ”function quiescence,” a widely used mechanism that permits updates only when a function is not on any active call stack. The authors argue this requirement is weak and insufficient for complex operating system updates. They illustrate this with an example inspired by the Linux fork implementation, where an update applied during function quiescence could still lead to an unsafe execution state, causing a function to be called twice instead of once. Prior attempts to solve this, such as pre-annotated transactions or static analysis, are dismissed as scaling poorly and placing a significant manual burden on programmers to verify correctness across all possible system states.

The survey then addresses the challenge of state transfer, identifying three dominant techniques used in prior work for C programs: type wrapping, object replacement, and shadow data structures. The paper contends that all three approaches fundamentally fail to properly and automatically handle pointers, particularly interior pointers (pointers to fields within a data structure) or stale base pointers. This failure is presented as a significant source of subtle logical errors and security vulnerabilities, including type-unsafe memory reads, writes to incorrect fields (similar to dangling pointer vulnerabilities), reading of stale data from old objects, and uninitialized reads from new data fields. While some solutions propose static analysis to identify these pointer-related issues, the authors argue this strategy is overly restrictive, scales poorly, limits common C idioms like void* pointers, and ultimately still requires unrealistic manual effort to manage long-lived pointers.

A third major limitation identified in existing solutions is the instability of the update process over time. Systems that load new code and data directly into the running version’s address space—an ”in-place” strategy—are shown to degrade. This approach introduces memory leakage, as reclaiming dead code and data is difficult, and poorer spatial locality due to address space fragmentation, leading to performance overhead that grows with each update. When surveying specific OS-level solutions, the paper critiques K42 for its unpredictable, deadlock-prone quiescence model and lack of automated state

transfer. It also examines Linux-based solutions like DynaMOS and LUCOS, criticizing their strategy of running old and new versions in parallel as unpredictable. Ksplice, which uses binary rewriting and shadow data structures, is acknowledged as an improvement but is criticized for lacking support for automated state transfer, state checking, hot rollback, or a more flexible definition of a safe update state beyond simple function quiescence.

The survey extends to user-space C programs, which are similarly criticized for using an in-place update model that fails to ensure a transactional or stable process and does not fully automate state transfer or checking. The paper also contrasts its approach with Kitsune, a contemporary system that also uses whole-program updates. It argues Kitsune's method of using shared libraries in the same address space fails to properly isolate or recover from errors during state transfer and possesses a less-capable state transfer mechanism that cannot handle interior pointers or automatically manage heap-allocated objects. The paper concludes its survey by positioning its own contributions—state quiescence, transactional process-level updates, and automated state management—as direct solutions to these identified gaps, drawing inspiration from prior work in dynamic modification systems, garbage collection, and program invariants. [8].

3.12 Integrated System and Process Crash Recovery in the Loris Storage Stack

The paper's survey of related work first addresses system crash recovery, comparing its TwinFS layout to other approaches. It positions TwinFS as a hierarchical version of doublefs or a selective copy-on-write (CoW) system where protected blocks have two pre-allocated copies. This design is noted to share advantages with CoW systems, such as avoiding redundant metadata writes and eliminating the need for complex metadata recovery code, but without suffering from high fragmentation or difficulty in tracking free space. The authors also situate their work in the context of fan-out stackable file systems like RAIF, which face similar global consistency problems but do not fully address them. Regarding data resynchronization, the paper compares its checksum-based log to journal-guided resynchronization. It argues that its approach is superior because the inclusion of checksums allows the system to determine not only what to resynchronize but also which of the redundant copies is valid and should be used, unlike earlier hash logs that were used for integrity but not resynchronization. The paper also acknowledges that solutions like ZFS eliminate the "write hole" problem entirely by never overwriting data.

The survey then transitions to process crash recovery, noting that little research has focused on storage stack reliability in microkernel environments, and existing studies depart radically from traditional models. The authors compare their in-memory logging and checkpointing approach primarily to Membrane, a system that uses a similar technique to recover file systems on Linux. The paper argues that its own approach, built on a microkernel, provides stronger guarantees and can recover from a broader class of failures due to strict process isolation. However, it also concedes that this comes at a higher performance cost. The authors differentiate their work by noting that they protect the complex RAID-equivalent (logical) layer, whereas Membrane protects the naming layer. Finally, the paper contrasts its solution with Re-FUSE, which can recover a more diverse set of file systems but only by making more assumptions about their correct behavior, whereas the Loris approach makes fewer assumptions about the internal state of the layers it protects. [6].

4 Literature Survey Summary

Sr. No	Year	Title	Advantages	Limitations
1	2013	Safe and Automatic Live Update for Operating Systems (PROTEOS)	Introduces "state quiescence" for safe update points. Implements transactional, process-level updates.	Does not update the core message-passing substrate. Requires manual annotations for ambiguous pointer scenarios.
2	2013	Integrated System and Process Crash Recovery in the Loris Storage Stack	Integrates system and process crash recovery using global metadata checkpoints. Provides fine-grained, corruption-resistant data resynchronization (solves write-hole). Uses in-memory roll-forward logging for process recovery.	Process crash recovery for naming and cache layers is future work. Efficient 'fsync' and transaction support is not yet implemented.
3	2009	Ksplice: Automatic Rebootless Kernel Updates	Provides automatic updates for small security patches in the Linux kernel. Works at the object-code level, simplifying patch analysis.	Limited to very small, simple patches. Does not support automated state transfer, state checking, or hot rollback. Relies on function quiescence.
4	2007	Reboots are for Hardware... (K42)	Supports live update in an object-oriented OS (K42).	Quiescence model is complex and can lead to deadlocks. Provides no support for automated state transfer. Techniques are limited to OO programs.
5	2006–2007	DyNaMOS / LUCOS	Applies code updates to the Linux kernel using binary rewriting.	Runs old and new code versions in parallel, leading to a highly unpredictable update process. State transfer is entirely manual.

Sr. No	Year	Title	Advantages	Limitations
6	2006–2009	Practical Dynamic Software Updating for C (Ginseng / Stump)	Provides dynamic update capabilities for user-space C programs.	Requires significant manual effort, code restructuring, and annotations. Does not provide a stable or transactional update process.
7	2012	Kitsune: Efficient, General-purpose Dynamic Software Updating for C	Implements whole-program updates for C programs.	Fails to properly isolate the state transfer process, so errors can corrupt the running program. State transfer mechanism is limited (e.g., no interior pointers).
8	2010	Membrane: Operating System Support for Restartable File Systems	Uses checkpoints and in-memory logging to recover file systems on Linux after a crash.	Provides weaker guarantees than Loris due to running on a monolithic kernel (no process isolation). Makes more assumptions about failure modes.
9	2011	Refuse to Crash with Re-FUSE	Provides crash recovery for a diverse range of FUSE file systems.	Makes more assumptions about the file system's correct behavior to achieve recovery, whereas Loris makes fewer.
10	2005	Journal-Guided Resynchronization for Software RAID	Improves RAID recovery speed by using the file system's journal to identify which blocks need resynchronization.	Solves *what* to resynchronize, but not *which* copy is valid. Still vulnerable to the "write hole" (corrupted data being copied over good data).
11	2004	Solaris ZFS File Storage Solution	A CoW (Copy-on-Write) file system that completely eliminates the "write hole" problem by never overwriting data in place.	CoW design has different performance trade-offs (e.g., potential for fragmentation). Loris aims to solve the write hole for traditional in-place update designs.

Sr. No	Year	Title	Advantages	Limitations
12	2007	doublefs: A COW-like Approach to File System Consistency	A layout that provides consistency by pre-allocating two locations for metadata blocks.	TwinFS (in Loris) is a hierarchical version of this, avoiding the need to read both copies of a block on every read.

Table 1: Literature Survey Summary for Fault-Tolerant Microkernel Research

5 System Architecture

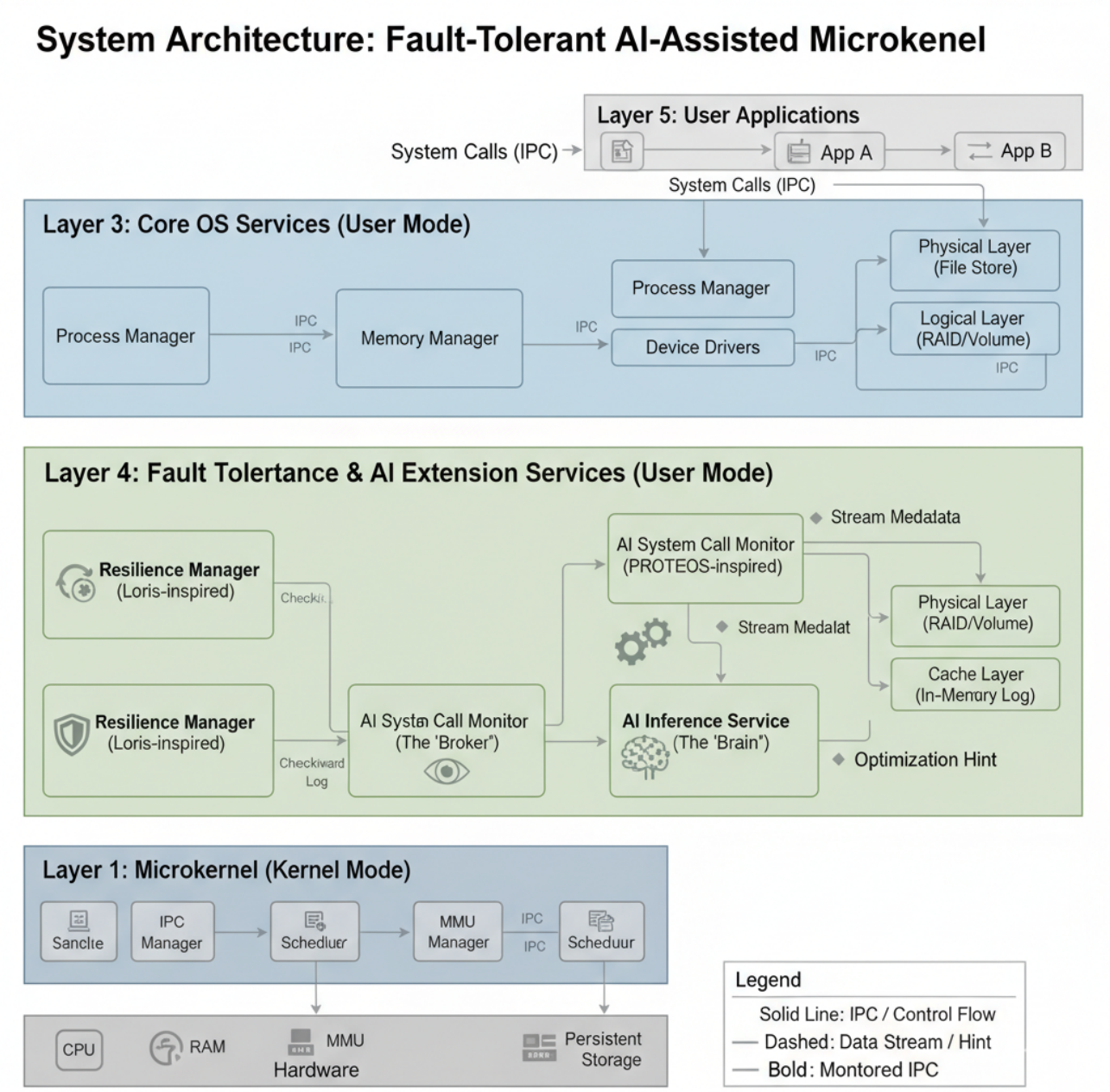

Figure 1: System Architecture

6 System Architecture: Fault-Tolerant Microkernel Extension with AI

This document outlines a system architecture for a fault-tolerant microkernel extension that integrates AI-assisted system calls. The design is heavily inspired by the concepts in the PROTEOS (live update) and Loris (crash recovery) papers, extending them with a predictive AI layer for enhanced resilience.

6.1 Core Architectural Philosophy

The system is built on a pure microkernel design. The kernel itself (running in kernel mode) is minimal. Its sole responsibilities are:

- **IPC (Inter-Process Communication):** Securely passing messages between processes.
- **Scheduling:** Basic, low-level process scheduling.
- **Hardware Abstraction:** Managing memory protection (MMU) and CPU traps/interrupts.

All traditional OS services (drivers, file systems, process management, and the new fault-tolerance components) run as isolated user-space processes (servers).

6.2 Key Architectural Components (Layers)

The system can be visualized in layers, from hardware up to applications.

6.2.1 Layer 1: Hardware

Standard CPU, Memory (MMU), Disks, Network Interface Cards (NICs).

6.2.2 Layer 2: Microkernel (Kernel Mode)

The minimal kernel, as described above. It is the single point of trust.

6.2.3 Layer 3: Core OS Services (User Mode)

These are the fundamental servers that provide OS functionality.

- **Process Manager:** Handles `fork`, `exit`, and `exec` requests.
- **Memory Manager:** Manages virtual memory mappings for all processes.
- **Device Drivers:** Individual, isolated processes for each piece of hardware (e.g., Disk Driver, Network Driver).
- **Loris-based Storage Stack:** A set of servers (as in the Loris paper) that manage storage.

Storage Stack Layers:

- *Physical Layer (File Stores):* Implements the on-disk layout with checkpointing support (like TwinFS).
- *Logical Layer (RAID):* Manages redundancy and data resynchronization.
- *Cache Layer:* Provides caching and in-memory roll-forward log for process crash recovery.

6.2.4 Layer 4: Fault-Tolerance & AI Extensions (User Mode)

This is the core of the proposed architecture. These are user-space servers that monitor and manage the Core OS Services.

1. Resilience Manager (Inspired by Loris):

- **Role:** Reactive crash recovery.
- **Function:** Acts as the "reincarnation server" for critical OS components.

Operation:

1. Subscribes to notifications from the microkernel about process deaths.
2. When a critical service crashes, the Resilience Manager is notified.
3. It restarts the crashed service and orchestrates recovery:
    - Instructs the new service to load from the last global metadata checkpoint.
    - Instructs the Cache Layer to replay its roll-forward log to restore pre-crash state.

2. Live Update Manager (Inspired by PROTEOS):

- **Role:** Proactive fault/downtime avoidance.
- **Function:** Manages planned, on-the-fly upgrades of services.

Operation:

1. Starts the new service in a standby state.
2. Waits for the old service to reach a "state quiescence" (safe update point).
3. Automates state transfer between the old and new instances.
4. Atomically switches IPC routing and terminates the old instance.

3. AI System Call Monitor (The "Broker"):

- **Role:** AI-based monitoring and interception.
- **Function:** Lightweight server acting as an intermediary for all user system calls.

Workflow:

1. All system calls from applications are routed to the AI Monitor.
2. The Monitor:
    - Forwards the system call to the target service.
    - Streams metadata (timestamp, source, target, call_type, args_hash) to the AI Inference Service.

4. AI Inference Service (The "Brain"):

- **Role:** Predictive fault and anomaly detection.
- **Function:** Analyzes real-time system call metadata using ML models.

AI Outputs:

- *Anomaly Detection:* Detects abnormal process behavior and alerts the Resilience Manager.
- *Predictive Prefetching:* Suggests prefetching of commonly accessed files to improve performance.
- *Scheduler Optimization:* Suggests priority adjustments based on predicted workload.

6.2.5 Layer 5: User Applications (User Mode)

Standard, unmodified applications that interact with the OS via IPC. They are unaware of the underlying AI and fault-tolerance mechanisms.

6.3 Key Interactions & Data Flows

1. Normal System Call Flow:

1. Application → Microkernel (e.g., message: read file "X")
2. Microkernel → AI Monitor (routes message)
3. AI Monitor → AI Inference Service (async metadata stream)
4. AI Monitor → Microkernel → File System (executes call)
5. Response flows back through the same path.

2. Process Crash (Reactive Recovery):

1. File System process crashes.
2. Microkernel notifies Resilience Manager.
3. Resilience Manager restarts the service via Process Manager.
4. New service loads from checkpoint; Cache Layer replays roll-forward log.
5. System returns to consistent state.

3. AI Anomaly (Predictive Recovery):

1. Application exhibits anomalous system call behavior.
2. AI Inference Service detects anomaly and alerts Resilience Manager.
3. Resilience Manager terminates or restarts the offending process.

4. Planned Update (Proactive Avoidance):

1. Administrator requests update via Live Update Manager.
2. Live Update Manager performs PROTEOS-style transactional upgrade.
3. Ensures zero downtime and state consistency during upgrade.

6.4 Methodology/Algorithms

- **Input:** System call logs, process execution traces, kernel crash reports, and performance metrics collected from the microkernel environment.
- **Step 1: Initialize**
  Set up the microkernel simulation environment. Initialize modules such as the Process Manager, Memory Manager, Resilience Manager, Live Update Manager, and AI Inference Service. Load baseline datasets for anomaly detection (system call frequency patterns, response times, and resource usage).
- **Step 2: System Initialization and Service Registration**
  1. Start the microkernel and launch core system services (Process Manager, Memory Manager, Device Drivers).
  2. Register the Fault-Tolerance and AI Monitoring servers (Resilience Manager, Live Update Manager, AI System Call Monitor, AI Inference Service).
  3. Establish Inter-Process Communication (IPC) channels between all servers.
- **Step 3: System Call Interception and Monitoring**
  1. All system calls from user applications are intercepted by the AI System Call Monitor.
  2. The Monitor forwards the request to the target OS service (e.g., File System or Scheduler) while simultaneously sending call metadata (timestamp, source PID, target service, operation type) to the AI Inference Service.
  3. Metadata is stored in an event buffer for further analysis.
- **Step 4: Fault Detection and Recovery (Reactive Phase)**
  1. The Microkernel detects a process crash and notifies the Resilience Manager.
  2. The Resilience Manager immediately restarts the crashed process using the Process Manager.
  3. The Resilience Manager instructs the Cache Layer to replay the in-memory roll-forward log to recover the last known consistent state.
  4. Once recovery completes, normal system operation resumes.
- **Step 5: Live Update Management (Proactive Phase)**
  1. The Live Update Manager handles planned updates of system components (e.g., File System or Memory Manager).
  2. It initiates a standby instance of the new service binary.
  3. Once the old instance reaches a quiescent state, the Manager transfers its state to the new instance.

4. The IPC routing is atomically switched to the new instance, achieving a live update with zero downtime.

- **Step 6: AI-Based Fault Prediction and Optimization**

  1. The AI Inference Service receives a continuous stream of system call data from the Monitor.
  2. A trained deep learning model (combining CNN for spatial patterns and LSTM for temporal dependencies) analyzes real-time system activity.
  3. If anomalous patterns are detected (e.g., unusual access frequency, unexpected service calls), the AI service alerts the Resilience Manager.
  4. The Resilience Manager can preemptively restart or isolate the affected service before a failure occurs.

- **Step 7: Predictive Scheduler and Resource Optimization**

  1. The AI Service also generates hints for process scheduling based on usage patterns.
  2. For example, compute-heavy tasks are prioritized dynamically to improve performance and prevent resource starvation.

- **Step 8: Continuous Learning and Feedback**

  1. System call data and recovery outcomes are logged and fed back to retrain the AI model periodically.
  2. This continuous feedback loop enhances prediction accuracy and adaptability for new fault types.

- **Step 9: Visualization and Reporting**

  1. Visualization tools present real-time metrics such as anomaly alerts, process uptime, and recovery latency.
  2. Reports are generated to evaluate overall system fault tolerance and predictive accuracy.

- **Step 10: End Algorithm.**

- **Resilience Manager Algorithm:** The Resilience Manager acts as the reactive recovery unit of the system. It constantly listens for process death notifications from the Microkernel. Upon detecting a crash, it initiates recovery steps that include spawning a replacement process, restoring checkpoints, and replaying the roll-forward cache log. This ensures that services return to their last consistent state with minimal downtime. The manager employs a recovery timer to ensure that repeated failures are flagged for AI-based diagnosis, integrating both reactive and predictive resilience mechanisms.

- **AI System Call Monitor:** The AI Monitor operates as an IPC-level interceptor that mirrors system call metadata to the AI Inference Service. This allows for near-zero latency inspection of all user-to-service communications. It ensures security and performance monitoring while remaining transparent to user processes. The design maintains isolation and minimal overhead by employing message-level forwarding rather than kernel hooks.

- **AI Inference Service (CNN-LSTM Model):** The AI layer employs a hybrid CNN-LSTM architecture. The Convolutional Neural Network (CNN) processes spatial dependencies between system services (e.g., file I/O sequences, memory access patterns), while the Long Short-Term Memory (LSTM) layer models temporal dependencies across time-series data of system calls. Together, they predict anomalous behavior or potential system faults. For example, if the LSTM layer detects unusual call frequencies or patterns inconsistent with trained behavior, it triggers a preemptive recovery action. The hybrid model enables both fast real-time predictions and long-term behavior understanding.

- **Live Update Manager (Inspired by PROTEOS):** This component handles proactive fault avoidance by safely replacing running system components without halting the system. It ensures that updates are transactional—either fully committed or fully rolled back—to prevent partial failures. The AI model can also suggest optimal update times based on observed load patterns.

- **Predictive Fault Recovery Workflow:** When the AI detects anomalies:

  1. The anomaly signal is sent to the Resilience Manager.
  2. The affected process is isolated, checkpointed, and restarted.
  3. Cache replay and consistency checks are triggered automatically.
  4. Logs of this event are used to refine AI model predictions.

  This workflow ensures minimal service interruption while maintaining data integrity.

6.5 Advantages and Disadvantages

Advantages:

1. **Enhanced Fault Tolerance:** The proposed microkernel extension integrates AI-driven fault prediction and recovery mechanisms, which minimize system downtime and prevent cascading failures in critical operations.
2. **Dynamic Error Handling:** Using machine learning models, the system can predict potential kernel faults and automatically trigger corrective actions, ensuring system stability and reliability.
3. **Modular and Scalable Design:** The microkernel architecture allows independent modules to operate with minimal dependencies. The AI layer enhances scalability by learning from new fault patterns without requiring major architectural changes.
4. **Improved System Reliability:** AI-assisted monitoring enables continuous analysis of kernel states, resource usage, and communication channels, leading to more stable system behavior and higher uptime.
5. **Adaptive Performance Optimization:** The integration of AI enables intelligent resource allocation, load balancing, and scheduling decisions to maintain optimal performance even under fault conditions.
6. **Proactive Maintenance:** The system's predictive learning capabilities help identify and mitigate issues before they lead to system crashes, reducing maintenance overhead and improving long-term dependability.
7. **Better Security Resilience:** AI-based anomaly detection mechanisms provide early warning against potential security breaches or abnormal kernel activity, adding an extra layer of system protection.

Disadvantages:

1. **High Computational Overhead:** Implementing AI-based fault detection and correction within the microkernel introduces additional processing requirements, which may affect system performance in low-power environments.
2. **Complex Implementation:** Integrating AI modules with kernel-level operations requires deep system-level expertise and careful design to avoid interference with core functionalities.
3. **Data Dependency:** The accuracy of AI fault prediction relies on the quality and quantity of system logs and historical data, which may be limited or inconsistent in certain embedded or legacy systems.
4. **Potential Latency:** Real-time systems may experience minor delays due to AI model inference times, which can impact applications where response time is critical.
5. **Maintenance and Retraining:** The AI components require continuous updates and retraining as new fault scenarios emerge, which adds to long-term system maintenance complexity.
6. **Debugging Difficulty:** The presence of AI-driven decision-making makes kernel debugging and error tracing more complex compared to traditional deterministic systems.

7. **Resource Constraints:** Deploying such an AI-extended microkernel on constrained devices (like IoT or embedded systems) can be challenging due to limited computational and memory resources.

7 Application

1. **Aerospace and Defense Systems:** Fault-tolerant microkernels with AI integration can be used in mission-critical aerospace and defense systems, where reliability and real-time decision-making are essential. AI algorithms can detect anomalies, predict potential hardware or software faults, and trigger corrective measures to maintain flight control stability and defense system responsiveness.
2. **Autonomous Vehicles:** AI-assisted fault-tolerant microkernels enhance the reliability of autonomous vehicles by monitoring critical system processes, detecting software crashes or sensor faults, and performing self-recovery in real time. This ensures continuous operation even under unpredictable environmental conditions or sensor malfunctions.
3. **Medical Devices and Healthcare Systems:** In life-critical systems such as patient monitoring and surgical robotics, AI-based microkernel fault management ensures continuous operation without system failure. The system can automatically isolate and recover from faults, thereby improving safety and patient outcomes.
4. **Industrial Automation and Robotics:** Manufacturing plants and robotic systems depend on real-time control. The AI-extended fault-tolerant microkernel enables predictive fault detection, process recovery, and dynamic load balancing, ensuring smooth, uninterrupted production lines and minimizing downtime.
5. **Cloud and Data Center Operations:** AI-driven fault-tolerant microkernels can manage virtualized workloads across distributed cloud environments. They predict node or service failures and automatically reassign tasks to maintain service continuity and improve infrastructure resilience.
6. **IoT and Edge Devices:** In resource-constrained IoT systems, AI-assisted fault prediction can identify faulty nodes, communication failures, or data inconsistencies early. This reduces device downtime, enhances network reliability, and extends the lifespan of IoT deployments.
7. **Operating Systems Research and Development:** The proposed model provides a framework for developing next-generation operating systems that integrate AI for kernel-level decision-making. This paves the way for adaptive, self-healing OS architectures suitable for high-reliability computing environments.
8. **Telecommunication Networks:** In large-scale communication systems, AI-based fault tolerance can detect and isolate malfunctioning network components within the kernel layer. This minimizes packet loss, maintains call quality, and ensures uninterrupted data transmission.

8 Conclusion

In conclusion, the proposed fault-tolerant microkernel extension with Artificial Intelligence (AI) enhances the reliability, security, and adaptability of modern operating systems. By integrating AI-driven fault detection, prediction, and recovery mechanisms directly into the kernel layer, the system ensures continuous operation even under unexpected hardware or software failures. The approach supports real-time self-diagnosis, autonomous recovery, and efficient resource management — key requirements for mission-critical environments such as aerospace, healthcare, and autonomous systems.

Furthermore, the modular and minimal design of the microkernel architecture improves system isolation, preventing localized failures from propagating across the system. The integration of AI enables proactive fault management, where potential errors are identified before they affect system stability. This combination of microkernel minimalism and intelligent adaptability positions the proposed model as a step toward next-generation self-healing operating systems.

The applications of this research extend across multiple domains, including embedded systems, industrial automation, cloud infrastructure, and IoT devices, demonstrating its scalability and versatility. Overall, this work contributes to advancing fault-tolerant computing by combining robust kernel design with adaptive AI mechanisms, creating a more resilient and intelligent system foundation for future computing platforms.

The future scope of this project involves expanding the AI-based fault management framework to support distributed and multi-core systems. Future developments could explore reinforcement learning and neural network models for dynamic fault classification and real-time recovery optimization. Additionally, integrating security-aware fault tolerance can enhance protection against malicious kernel-level failures. Implementing the model across heterogeneous hardware and testing it under real-world workloads will further validate its effectiveness, paving the way for fully autonomous and self-healing operating systems in critical computing environments.

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