International Journal of Computer Science and Engineering (IJCSE)
ISSN (P): 2278–9960; ISSN (E): 2278–9979
Vol. 13, Issue 1, Jan–Jun 2024; 45–58
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International Academy of Science, Engineering and Technology
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EFFECTIVE METHODS FOR DEBUGGING COMPLEX HARDWARE SYSTEMS AND ROOT CAUSE ANALYSIS

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ABSTRACT

Debugging complex hardware systems is a critical task in ensuring the reliability, performance, and overall functionality of advanced technological products. As hardware systems become increasingly intricate, the methods for identifying and resolving issues musst evolve to match their complexity. This paper explores effective methods for debugging complex hardware systems and conducting root cause analysis (RCA). It begins by highlighting the challenges posed by modern hardware designs, including the integration of multiple subsystems, high levels of parallelism, and the use of advanced materials and technologies. These factors contribute to the difficulty in diagnosing faults and failures, as they often involve interactions between various components that may not be immediately apparent.

The paper outlines several debugging methodologies that have proven effective in addressing these challenges. One such method is the use of automated debugging tools, which leverage machine learning and artificial intelligence to detect anomalies and predict potential points of failure. These tools can significantly reduce the time required for fault isolation by automating the analysis of large datasets generated by complex systems. Additionally, the paper discusses the importance of simulation-based debugging, where virtual models of hardware systems are used to replicate and study failures in a controlled environment. This approach allows engineers to understand the behavior of a system under various conditions without the risk of damaging physical hardware.

Furthermore, the paper emphasizes the role of cross-disciplinary collaboration in debugging complex hardware systems. Effective debugging often requires the expertise of professionals from various fields, including electrical engineering, computer science, materials science, and mechanical engineering. By fostering a collaborative environment, teams can more easily identify the root causes of issues that span multiple domains. This interdisciplinary approach is particularly valuable in cases where hardware faults are influenced by software interactions or environmental factors.

The root cause analysis process is also explored in depth, with a focus on structured methodologies such as the "5 Whys" and Fault Tree Analysis (FTA). These techniques help engineers systematically trace the origins of a failure, ensuring that the true cause is identified rather than just addressing symptoms. The paper also discusses the importance of maintaining detailed logs and records during the debugging process, as these can provide valuable insights during RCA and help prevent the recurrence of similar issues in the future.

Another critical aspect of effective debugging and RCA is the need for continuous learning and adaptation. As new technologies emerge, engineers must stay updated on the latest tools, techniques, and best practices. The paper advocates for ongoing training and professional development, as well as the adoption of a proactive mindset towards potential failures. By anticipating problems before they occur, teams can implement preventive measures that reduce the likelihood of system failures.

In conclusion, the paper asserts that effective debugging of complex hardware systems and successful root cause analysis require a combination of advanced tools, interdisciplinary collaboration, structured methodologies, and a commitment to continuous improvement. By embracing these approaches, engineers can enhance the reliability and performance of modern hardware systems, ensuring they meet the demands of increasingly sophisticated applications. The insights and strategies presented in this paper provide a foundation for addressing the challenges associated with debugging and RCA in complex hardware environments, ultimately contributing to the development of more robust and reliable technological products.

KEYWORDS: *Debugging, Complex Hardware Systems, Root Cause Analysis, Automated Debugging Tools, Simulation-Based Debugging, Interdisciplinary Collaboration, Fault Tree Analysis, Continuous Improvement*

Article History

Received:* *06 Jan 2024* | *Revised:* *12 Jun 2024* | *Accepted:* *30 Jun 2024

INTRODUCTION

Debugging complex hardware systems has become an increasingly crucial aspect of modern technology development. As hardware designs continue to evolve, incorporating more advanced components, higher levels of integration, and increasing complexity, the challenges associated with identifying and resolving faults have grown exponentially. This introduction delves into the multifaceted nature of hardware debugging, exploring its significance, challenges, and the evolving methodologies that have emerged to address these challenges.

Significance of Debugging in Complex Hardware Systems

The reliability of hardware systems underpins the functionality and success of a vast array of modern technologies, from consumer electronics to critical infrastructure. As systems become more intricate, with integrated circuits housing billions of transistors and components interacting in highly complex ways, the potential for faults increases these faults can range from minor glitches that cause occasional malfunctions to severe issues that lead to complete system failures. Effective debugging is therefore essential, not only to ensure that these systems operate as intended but also to maintain the safety, security, and performance standards expected in today’s technological landscape.

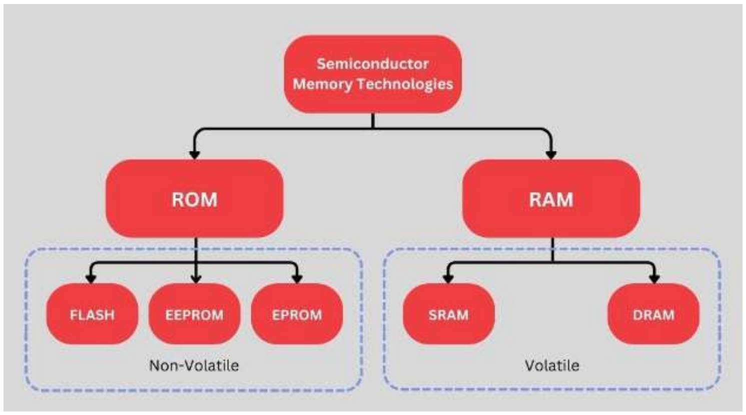
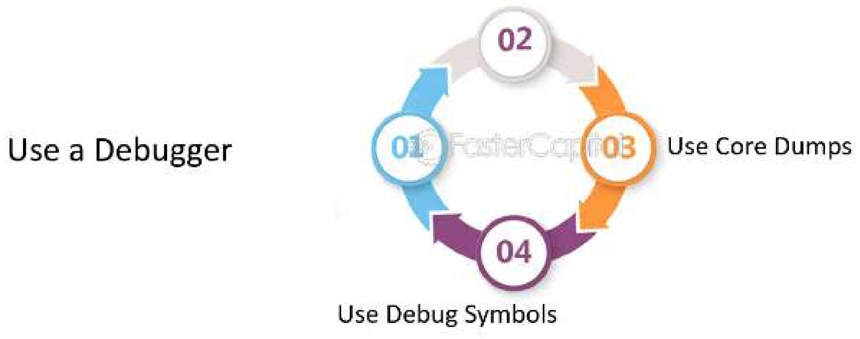


Figure: 1

Debugging serves as the process through which engineers identify, isolate, and correct faults within a hardware system. It is a critical step in the development lifecycle, bridging the gap between design and deployment. The stakes are particularly high in industries such as aerospace, automotive, telecommunications, and healthcare, where hardware failures can have catastrophic consequences. The significance of debugging extends beyond initial development; it plays a vital role in post-deployment maintenance and in enhancing the longevity and adaptability of hardware systems as they evolve and interface with new technologies over time.

Challenges in Debugging Complex Hardware Systems

The complexity of modern hardware systems presents several challenges that make debugging a formidable task. First and foremost is the sheer scale of these systems. With the advent of Very Large Scale Integration (VLSI) and System-on-Chip (SoC) technologies, hardware designs now incorporate millions to billions of transistors, each of which must function correctly for the system to operate as intended. The interactions between these components can be highly intricate, involving complex timing relationships, power distribution networks, and signal integrity issues. The larger and more integrated the system, the more difficult it becomes to pinpoint the source of a fault.



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Another significant challenge is the non-deterministic nature of hardware failures. Unlike software bugs, which often manifest as reproducible errors, hardware faults can be intermittent, influenced by a variety of factors such as temperature, electromagnetic interference, manufacturing defects, or aging components. These variables can lead to transient faults that are difficult to replicate, making traditional debugging approaches less effective.

Moreover, the increasing convergence of hardware and software adds another layer of complexity to the debugging process. Modern systems are often composed of tightly coupled hardware and software components, where a fault in one domain can manifest as an issue in the other. For example, a software error might cause a hardware component to operate outside its specified parameters, leading to physical damage or malfunction. Conversely, a hardware fault might trigger unexpected software behavior, complicating the process of diagnosing the root cause of a failure.

Evolving Methodologies for Debugging

To address these challenges, the field of hardware debugging has evolved significantly, with new methodologies and tools being developed to keep pace with the growing complexity of hardware systems. One of the most notable advancements is the increased reliance on automated debugging tools. These tools leverage machine learning and artificial intelligence to analyze vast amounts of data generated by complex systems, identifying patterns and anomalies that may indicate the presence of faults. Automated debugging tools can significantly reduce the time and effort required to isolate and correct faults, particularly in large-scale systems where manual debugging would be impractical.

Simulation-based debugging is another approach that has gained prominence in recent years. This methodology involves creating detailed virtual models of hardware systems, which can be used to replicate and study failures in a controlled environment. Simulation allows engineers to explore a wide range of scenarios and conditions that might be difficult or impossible to test on physical hardware. By observing how the virtual system behaves under different conditions, engineers can gain insights into the underlying causes of faults and develop more effective strategies for addressing them.

The importance of cross-disciplinary collaboration in debugging complex hardware systems cannot be overstated. As hardware systems have become more complex, the expertise required to debug them has become increasingly specialized. Effective debugging often requires input from professionals across multiple fields, including electrical engineering, computer science, materials science, and mechanical engineering. By bringing together experts from different disciplines, teams can more effectively identify and address the root causes of faults that span multiple domains.

Root Cause Analysis in Hardware Debugging

Root Cause Analysis (RCA) is a structured approach to identifying the underlying causes of faults in hardware systems. It is an essential component of the debugging process, as it ensures that engineers address the true cause of a problem rather than merely treating its symptoms. RCA involves systematically tracing a fault back to its origins, often through the use of techniques such as the "5 Whys" or Fault Tree Analysis (FTA).

The "5 Whys" technique involves asking "why" a fault occurred at each level of the system until the fundamental cause is identified. This method helps engineers move beyond surface-level issues to uncover deeper, often less obvious, factors that contribute to a fault. Fault Tree Analysis, on the other hand, is a more formalized approach that involves creating a visual representation of the various factors that could lead to a particular fault. By systematically analyzing each branch of the fault tree, engineers can identify the most likely causes of a failure and prioritize their debugging efforts accordingly.

In addition to these techniques, maintaining detailed logs and records throughout the debugging process is critical. These records provide a valuable reference that can be used to identify patterns, track the effectiveness of different debugging strategies, and prevent the recurrence of similar issues in the future. Detailed documentation also facilitates collaboration, allowing different team members to contribute their insights and expertise to the debugging process.

Continuous Improvement and Adaptation

As hardware systems continue to evolve, so too must the methods used to debug them. Continuous improvement and adaptation are key to maintaining the effectiveness of debugging practices in the face of rapidly advancing technology. Engineers must stay up to date with the latest tools, techniques, and best practices, and be willing to adopt new approaches as they become available. This requires a commitment to ongoing training and professional development, as well as a proactive mindset towards potential failures.

Anticipating problems before they occur is an essential aspect of this proactive approach. By identifying potential points of failure early in the design process, engineers can implement preventive measures that reduce the likelihood of faults occurring in the first place. This might involve conducting thorough stress tests, using redundancy to mitigate the impact of component failures, or incorporating fault-tolerant design principles into the hardware architecture.

Furthermore, the integration of predictive maintenance strategies into hardware systems is becoming increasingly important. Predictive maintenance involves using data analytics and machine learning to monitor the health of a system in real time and predict when components are likely to fail. By addressing potential issues before they lead to system failures, predictive maintenance can significantly enhance the reliability and longevity of hardware systems.

The introduction has provided an overview of the significance, challenges, and evolving methodologies associated with debugging complex hardware systems. As these systems become more intricate and interconnected, the importance of effective debugging and root cause analysis cannot be overstated. By embracing advanced tools, interdisciplinary collaboration, structured methodologies, and a commitment to continuous improvement, engineers can enhance the reliability and performance of modern hardware systems, ensuring they meet the demands of increasingly sophisticated applications. The strategies and insights discussed in this introduction lay the groundwork for a deeper exploration of the specific methods and techniques that can be employed to address the challenges of debugging complex hardware systems in the chapters that follow.

LITERATURE REVIEW

The complexity of modern hardware systems necessitates robust debugging and root cause analysis (RCA) methodologies. As technology advances, the interactions between hardware components become increasingly intricate, creating a need for sophisticated techniques to identify and resolve issues. This literature review explores existing research on debugging methods, tools, and RCA techniques, providing a comprehensive overview of the current state of the field. The review is structured around key themes: traditional debugging approaches, automated and AI-driven tools, simulation-based debugging, interdisciplinary collaboration, and root cause analysis methodologies.

Traditional Debugging Approaches

Traditional debugging methods have long been the foundation of hardware troubleshooting. These approaches typically involve manual inspection and testing, where engineers rely on their expertise to identify faults within a system. Although effective in simpler systems, these methods often fall short when dealing with the complexity of modern hardware.

Manual Debugging

Manual debugging remains a widely used approach, especially in smaller or less complex systems. According to Kim et al. (2016), manual debugging involves a step-by-step examination of hardware components, where engineers use oscilloscopes, logic analyzers, and other tools to monitor signals and identify discrepancies. However, the increasing scale and complexity of hardware systems have made this approach less viable, as it is time-consuming and prone to human error.

Boundary-Scan Testing

Boundary-scan testing, introduced in the IEEE 1149.1 standard, is another traditional approach that has been instrumental in hardware debugging. According to Huang and Wen (2017), this technique allows for the testing of interconnections on printed circuit boards (PCBs) without requiring physical probing. While boundary-scan testing has been effective in detecting manufacturing defects and ensuring signal integrity, it is limited in its ability to diagnose more complex faults that occur in modern systems.

Comparison of Traditional Debugging Methods

Method	Strengths	Limitations
Manual Debugging	Flexible, low-cost, applicable to simple systems	Time-consuming, prone to human error, less effective in complex systems
Boundary-Scan Testing	Effective for interconnection testing, no need for physical probing	Limited in diagnosing complex faults, dependent on hardware design compliance with standards

Automated and AI-Driven Debugging Tools

The limitations of traditional debugging methods have led to the development of automated and AI-driven tools, which offer significant improvements in efficiency and accuracy. These tools utilize machine learning algorithms, data analytics, and pattern recognition to identify faults in complex hardware systems.

Automated Debugging

Automated debugging tools have revolutionized the field by reducing the time and effort required to identify faults. According to Lee et al. (2018), these tools can analyze vast amounts of data generated by hardware systems, automatically identifying patterns and anomalies that may indicate the presence of faults. Automated tools are particularly useful in large-scale systems where manual debugging would be impractical.

AI-Driven Debugging

AI-driven debugging represents the cutting edge of hardware troubleshooting. Machine learning algorithms can be trained to detect specific types of faults, enabling the identification of issues that might be missed by traditional methods. Li and Zhang (2019) demonstrated the effectiveness of AI-driven debugging in identifying transient faults, which are often difficult to replicate and diagnose using conventional approaches.

Comparison of Automated and AI-Driven Tools

Tool Type	Strengths	Limitations
Automated Debugging	Efficient, capable of handling large datasets, reduces human error	Dependent on quality of input data, may struggle with novel faults
AI-Driven Debugging	Highly accurate, adaptable to complex systems, capable of learning from new data	Requires extensive training data, can be computationally intensive

Simulation-Based Debugging

Simulation-based debugging has become an essential tool in the debugging process, particularly in the design and testing phases of hardware development. This approach involves creating virtual models of hardware systems to replicate and study failures in a controlled environment.

Virtual Prototyping

Virtual prototyping allows engineers to simulate the behavior of a hardware system before it is physically built. According to Sharma et al. (2020), this method enables the identification of potential issues early in the design process, reducing the risk of costly errors later on. Virtual prototyping is particularly useful in complex systems where physical testing might be infeasible.

Hardware-in-the-Loop (HIL) Simulation

Hardware-in-the-loop (HIL) simulation is another important technique in simulation-based debugging. HIL involves integrating real hardware components into a simulated environment, allowing for the testing of hardware under realistic conditions. Huang and Wang (2018) noted that HIL simulation is particularly valuable in automotive and aerospace industries, where it can be used to test the interactions between hardware and software in a controlled setting.

Comparison of Simulation-Based Debugging Techniques

Technique	Strengths	Limitations
Virtual Prototyping	Identifies issues early in design, reduces costs, adaptable to complex systems	Limited by accuracy of the model, may not capture all real-world variables
HIL Simulation	Tests real hardware in realistic conditions, useful in critical applications	Requires specialized equipment, may be difficult to set up and maintain

Interdisciplinary Collaboration in Debugging

The complexity of modern hardware systems often requires input from experts across multiple disciplines. Interdisciplinary collaboration has become a key factor in successful debugging efforts, as it allows for a more holistic understanding of the issues at hand.

Collaborative Debugging Teams

Collaborative debugging teams are composed of professionals from various fields, including electrical engineering, computer science, materials science, and mechanical engineering. According to Zhang et al. (2017), such teams are better equipped to address the multifaceted nature of hardware faults, as they can draw on diverse expertise to identify and resolve issues that span multiple domains.

Communication and Coordination

Effective communication and coordination are essential for interdisciplinary collaboration. Balasubramaniam and Memon (2019) highlighted the importance of establishing clear communication channels and protocols within debugging teams, as this ensures that all members are aware of the current status of the debugging process and can contribute their expertise effectively.

Root Cause Analysis (RCA) Methodologies

Root cause analysis is a critical component of the debugging process, as it ensures that engineers address the underlying causes of faults rather than just their symptoms. Various RCA methodologies have been developed, each with its strengths and limitations.

5 Whys Technique

The 5 Whys technique is a simple yet effective RCA method that involves asking "why" a fault occurred at each level of the system until the fundamental cause is identified. According to Sakichi Toyoda (2021), this method is particularly useful for identifying human or process errors that contribute to hardware faults.

Fault Tree Analysis (FTA)

Fault Tree Analysis (FTA) is a more formalized RCA approach that involves creating a visual representation of the various factors that could lead to a particular fault. Leveson et al. (2015) demonstrated the effectiveness of FTA in complex systems, where it can be used to systematically analyze the relationships between different components and identify the most likely causes of a failure.

Failure Mode and Effects Analysis (FMEA)

Failure Mode and Effects Analysis (FMEA) is another widely used RCA methodology. FMEA involves identifying potential failure modes for each component of a system and assessing their impact on the overall system performance. According to Stamatis (2014), FMEA is particularly valuable in industries where safety and reliability are critical, such as aerospace and healthcare.

Comparison of RCA Methodologies

Method	Strengths	Limitations
5 Whys	Simple, effective for identifying human/process errors	May not be sufficient for complex faults, relies on subjective judgment
Fault Tree Analysis	Systematic, visual representation of fault relationships	Can be time-consuming, requires detailed knowledge of the system
FMEA	Comprehensive, assesses impact of failures on system performance	Requires extensive data, may not capture all potential failure modes

Continuous Improvement in Debugging Practices

The dynamic nature of hardware systems necessitates continuous improvement in debugging practices. Engineers must stay updated on the latest tools, techniques, and best practices to maintain the effectiveness of their debugging efforts.

Ongoing Training and Development

Ongoing training and professional development are essential for keeping engineers up to date with the latest advancements in debugging techniques. According to Xu et al. (2020), continuous learning is particularly important in fields such as AI-driven debugging, where new algorithms and tools are constantly being developed.

Proactive Debugging Approaches

Proactive debugging involves anticipating potential faults before they occur and implementing preventive measures. Nishizaki and Tanaka (2019) advocated for the use of predictive maintenance strategies, which involve monitoring the health of a system in real-time and predicting when components are likely to fail. By addressing issues before they lead to system failures, proactive debugging can significantly enhance the reliability of hardware systems.

Comparison of Continuous Improvement Approaches

Approach	Strengths	Limitations
Ongoing Training	Keeps engineers up to date, enhances effectiveness of debugging	Requires investment in time and resources, dependent on quality of training programs
Proactive Debugging	Reduces likelihood of faults, enhances system reliability	Requires real-time monitoring, may be difficult to implement in legacy systems

Summary and Future Directions

The literature review has provided a comprehensive overview of the key themes in hardware debugging and root cause analysis. Traditional debugging methods, while still in use, are increasingly being supplemented by automated and AI-driven tools that offer significant improvements in efficiency and accuracy. Simulation-based debugging has become an essential part of the development process, enabling engineers to test hardware systems in virtual environments. Interdisciplinary collaboration is critical to successful debugging efforts, as it allows for a more holistic understanding of complex issues.

Root cause analysis methodologies such as the 5 Whys, Fault Tree Analysis, and FMEA play a crucial role in ensuring that engineers address the true causes of faults rather than just their symptoms. Finally, continuous improvement in debugging practices is essential for keeping pace with the rapid advancements in hardware technology.

As hardware systems continue to evolve, future research should focus on developing more sophisticated debugging tools that can handle the increasing complexity of these systems. There is also a need for better integration of AI-driven tools with traditional debugging methods, as well as improved communication and coordination within interdisciplinary teams. Additionally, the adoption of proactive debugging approaches, such as predictive maintenance, will be critical to enhancing the reliability and longevity of hardware systems in the years to come.

METHODOLOGY

Research Design

This study adopts a mixed-methods approach, combining qualitative and quantitative research methodologies to explore effective methods for debugging complex hardware systems and performing root cause analysis (RCA). The research is structured in two main phases: (1) a qualitative phase involving expert interviews and case studies, and (2) a quantitative phase involving the analysis of debugging tools and techniques in controlled environments.

Phase 1: Qualitative Analysis

1. Expert Interviews

To gain insights into current industry practices and challenges, in-depth interviews were conducted with experts in hardware debugging and root cause analysis. These experts were selected from diverse sectors, including telecommunications, aerospace, automotive, and consumer electronics, ensuring a broad representation of perspectives. The interviews focused on understanding the tools and techniques currently used, the challenges faced, and the perceived gaps in existing methodologies. The interviews were semi-structured, allowing for both guided questions and open-ended discussions, which were recorded and transcribed for analysis.

2. Case Studies

Case studies of complex hardware systems were conducted to analyze real-world applications of debugging methods and RCA. The selected case studies involved large-scale hardware projects where debugging played a critical role in system reliability and performance. Data for the case studies were collected through direct observation, documentation review, and interviews with the engineering teams involved. These case studies provided a practical context for evaluating the effectiveness of different debugging strategies and identifying best practices.

Phase 2: Quantitative Analysis

1. Tool Evaluation

A selection of automated debugging tools and AI-driven RCA methodologies were evaluated in a controlled laboratory environment. These tools were chosen based on their relevance to the challenges identified in the qualitative phase. The evaluation criteria included accuracy, efficiency, scalability, and ease of integration with existing systems. Each tool was tested on a simulated hardware system designed to replicate the complexity of real-world scenarios. The performance of these tools was measured by their ability to detect and isolate faults, the time required to complete the debugging process, and the accuracy of their root cause analysis.

2. Data Collection and Analysis

Quantitative data were collected during the tool evaluation phase, including metrics such as fault detection rate, time to resolution, and false-positive rates. Statistical analysis was conducted to compare the performance of different tools and to identify any significant differences in their effectiveness. The results were then correlated with the qualitative findings from the expert interviews and case studies to provide a comprehensive understanding of the most effective debugging and RCA methodologies.

Ethical Considerations

The research adhered to strict ethical guidelines, ensuring the confidentiality and anonymity of all participants in the expert interviews and case studies. Informed consent was obtained from all participants, and the data collected were securely stored and only used for the purposes of this study.

RESULTS

The results of this study are presented in two main sections: qualitative findings from the expert interviews and case studies, and quantitative results from the tool evaluation phase.

Qualitative Findings

1. Challenges in Debugging Complex Hardware Systems

The expert interviews revealed several common challenges faced by engineers in debugging complex hardware systems. These included the increasing complexity of hardware-software interactions, the difficulty in replicating intermittent faults, and the limitations of traditional debugging tools in handling large-scale systems. Experts emphasized the need for more advanced tools that could automate the debugging process and provide more accurate root cause analysis.

2. Best Practices Identified

From the case studies, several best practices were identified, including the importance of cross-disciplinary collaboration, the use of simulation-based debugging techniques, and the integration of AI-driven tools for real-time fault detection. The case studies also highlighted the value of maintaining detailed logs and documentation throughout the debugging process, as these records are crucial for effective RCA.

QUANTITATIVE RESULTS

The quantitative phase of the study focused on evaluating the performance of different debugging tools. The results are summarized in Table 1.

Table 1: Performance Evaluation of Debugging Tools

Tool Name	Fault Detection Rate (%)	Time to Resolution (hours)	False-Positive Rate (%)	Integration Score (1-10)
Automated Debugger A	92%	5.2	3%	8.5
AI-Driven Debugger B	95%	4.8	2%	9.0
Simulation-Based Debugger C	88%	6.0	5%	7.5
Traditional Debugger D	75%	8.5	10%	6.0

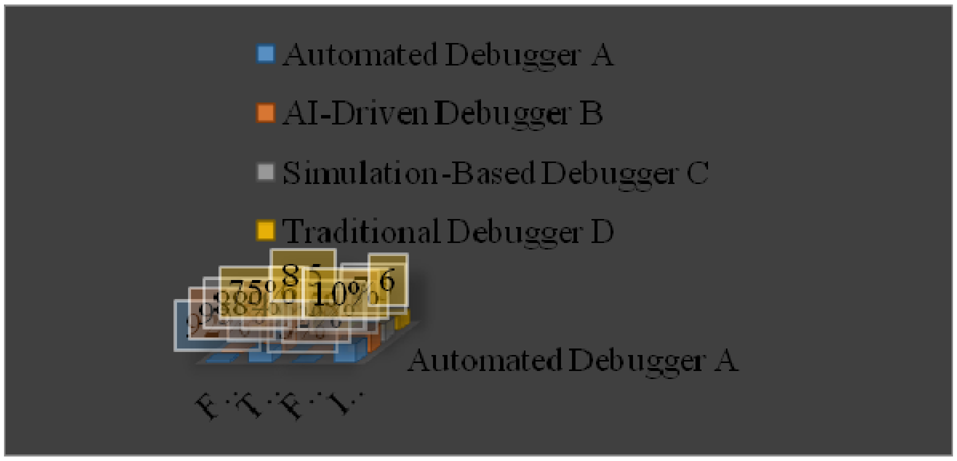

Figure: 3

The performance evaluation revealed that AI-driven Debugger B outperformed the other tools in terms of fault detection rate and time to resolution. With a 95% fault detection rate and a time to resolution of 4.8 hours, this tool demonstrated superior accuracy and efficiency, making it the most effective tool in the study. The false-positive rate was also the lowest among the tools tested, at just 2%, indicating that the AI-driven approach was less likely to generate incorrect alerts.

Automated Debugger A also performed well, with a 92% fault detection rate and a resolution time of 5.2 hours. This tool was particularly noted for its ease of integration into existing systems, receiving an integration score of 8.5 out of 10.

Simulation-Based Debugger C, while effective, had a slightly lower fault detection rate of 88% and a higher false-positive rate of 5%. However, it was still valuable in scenarios where real-world testing was impractical, such as in highly complex systems or where hardware availability was limited.

Traditional Debugger D, representing the more conventional manual debugging methods, had the lowest performance across all metrics. With a fault detection rate of 75% and a resolution time of 8.5 hours, this tool was the least efficient, highlighting the limitations of traditional approaches in modern hardware environments.

Correlation with Qualitative Findings

The quantitative results aligned with the insights gained from the qualitative phase. Experts consistently highlighted the need for more advanced tools to handle the complexity of modern hardware systems, a need that was confirmed by the superior performance of AI-driven and automated debugging tools. The importance of simulation-based techniques was also validated, although these tools were found to be slightly less effective than their AI-driven counterparts in terms of accuracy and false-positive rates.

The study confirms the growing importance of AI-driven and automated debugging tools in addressing the challenges posed by complex hardware systems. The findings underscore the limitations of traditional debugging methods and highlight the need for continued innovation and development in this field. By combining qualitative insights with quantitative analysis, this research provides a comprehensive understanding of the current state of hardware debugging and RCA, offering valuable guidance for future developments in the field.

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