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Robust Control Systems in Harsh Environments

***Adedeji, W.O.**
Department of Mechatronics Engineering, Osun State University.

***Corresponding author email**: wasiu.adedeji@uniosun.edu.ng

Abstract
Operating in extreme conditions, where the surrounding is extreme temperatures, dust formation, mechanical vibrations, and unreliable power access, the strong control systems are essential to the positive functioning of the production process in the sphere of manufacturing, mining, logistics, and energy. This type of circumstances, which prevails in textile mills, mining areas and out-of-system logistics ports, results in equipment malfunctions, disruption of the process and efficiency loss; traditional control systems report 10-15 percent of downtime and 5-10 percent error rates. This work thus envisions, deploys and tests low-cost, scalable robust control systems, which makes use of open-source microcontrollers (such as Arduino using H-infinity control) and Programmable Logic Controllers (PLCs) to achieve stability and efficiency under environmental uncertainty conditions. The methodology used is the mixed-method approach since it incorporated a systematic literature search of 60 peer-reviewed articles (2019-2025), semi-structured interviews with 20 industry players, surveys of 100 organisations, and two case studies of Nigerian businesses. The results show an increase of 25 to 35 percent of system reliability, 20 to 30 percent of productivity, 15 to 25 percent of cost savings, as well as return on investment exceeding 1500 percent over a six-month period. Scalability facilitates the act of expansion of the operations, whereas a stable state with extreme conditions is ensured by the use of H-infinity, sliding-mode, and adaptive PI controls. The barriers to adoption include lack of skills, infrastructure barriers, integration challenges and organisation resistance. The dissertation also provides detailed frameworks to be used by industry stakeholders, policymakers and researchers to advance the robust control systems to foster resilience and competitiveness in the Industry 4.0 paradigm. It will fill an important gaps and provide empirical knowledge, theoretical ideas, and practical solutions that enable an operation in severe conditions.

Keywords: Robust, Control, Harsh, Environmental, Logistics..

Introduction

Under hostile conditions, which can be considered in terms of 100-degree temperatures, dust-filled environment, mechanical vibration, or poorly reliable electricity, significant operational problems in the manufacturing, mining, logistic, and energy industries can be observed and denoted by failures of equipment, disruption of the process, and essential efficiency losses. These are operated in a variety of industrial environments, such as textile mills with dust accumulation, mining sixty sites with dust-producing particulates and high temperatures, logistics centres subjected to outdoor weather changes, and energy plants with irregular power systems, and as a result, they standards dual the maintenance costs by 1520 percent and cause 1015 percent outage in traditional control systems (Kumar, & Singh, 2023). In Nigeria, other regional limitations that industries face include power outages that cover 70 per cent of its operation and high dust concentrations in manufacturing areas, which further increase the cost of maintenance and operational attacks (World Bank, 2020; Gupta & Sharma, 2022). To take an example, in Sub-Saharan Africa textile factories the sensor degrades on dust, so a 5-10 percent error rate in process monitoring, and logistics experiences delays due to power outbursts that reduce the efficiency of delivery by 10-15 percent (Moreira et al., 2024). In the same way, slack productivity is evident in the German automotive manufacturing and American energy production, where oscillations and power-imbalance are the predictable results (Patel & Lee, 2023).

Rigid control systems are meant to ensure that stability and performance during the environmental uncertainties thus necessarily becoming essential in industries that work in a harsh environment. Such systems use advanced methods of control as H-infinity control, sliding-mode control, and adaptive PID tuning to eliminate disturbances in the form of vibrations, temperature differences, and surges of power (Zhou 2021). As an example, H-infinity control minimises manufacturing machinery errors in operations prone to vibrations and consists of 95% reliability in the system, adaptive PID tuning minimises logistics processes in the event of power outages, and can reduce downtime by 1520 percent (Skogestad & Postlethwaite, 2020). A powerful control system can maintain the stability of a conveyor belt when it is affected by noise of the sensors due to dust, which in turn leads to an increase in throughput by 2025 percent (Santos & Ferreira, 2023). In contrast to traditional control systems that tend to collapse under extreme circumstances, robust control systems can make use of mathematical models to minimise system response based on which a system can by and large operate well under various industrial environments (Chen & Zang, 2022). Robust control systems used commercially (including those built into industrial automation systems like Siemens or Rockwell Automation) cost prohibitively, starting at $50,000 and up to 150,000, and maintenance as much as $10,000 to 20,000 annually (Kumar & Zang, 2023). They are designed to operate well in large businesses that have a large budget and technical skills, which makes them unaffordable to the smaller organisations, such as SMEs and mid-size logistics companies, which make up 90% of the businesses in the developing world (World Bank, 2020). As an illustration, a control system will not be cost-effective to an SME with an annual budget of 100,000 dollars, even though the company might save more money due to the downtime reduction (Gupta & Sharma, 2022). Affordable alternatives consist of open-source microcontrollers (Arduino or RaspberryPI), more cost-effective PLCs, and can be installed between 300 and 1,000 dollars, and allows one to deploy scalable and resilient robust control systems targeting harsh environments (Li and Chen, 2021). Examples of these technologies include helping one to scale up the production lines during the manufacturing industry or tracking the various logistics locations, without performance degradation.

The COVID-19 pandemic revealed the risk in those industries that function in harsh environments with 50-percent responding that they lost over 20-percent of their revenues due to equipment failures, disruption in supply chains, and labour shortage (World Bank, 2020). The textile manufacturing and mining industry underwent a transit closure in Nigeria causing conditions to emphasize the shortcomings of manual or aging control systems (Moreira et al., 2024). Indicatively, a freighting company based in South Africa has reported 15 per cent delays in deliveries due to power outage, highlighting why automation needs to be resilient (Santos & Ferreira, 2023). The challenges are overcome through robust control systems, which include fault-tolerant and adaptive controls which ensure stability even when disturbances in the environment are observed. The manufacturing plant with a sound control system will be able to maintain the working of machinery during vibrations, also saving the time on the downtime by 15-20% whereas a logistics operation will be able to maintain the accuracy of the GPS tracking during the relapses of power and thus raise the efficiency by 15% (Patel & Lee, 2023).

Financial limitations, technical complexity, resistance in organisations and infrastructural limitations prevent implementation of robust control systems. Initial heavy costs and service maintenance costs limit the small organisations, and the need to apply the control theory and programming skills presents an important drawback (Li & Chen, 2021). Nigerian industries have no skilled staff to make it harder to implement (Gupta & Sharma, 2022). Fifty per cent of industries face organisational resistance presence in terms of job replacement and low technical literacy particularly in the traditional industries including manufacturing and mining (Smith & Johnson, 2022). The unreliable power or internet connectivity threatens 10-15 percent downtime in automated systems, particularly in developing territories (World 2020). The thesis will develop and experiment low-cost, scalable, and robust module controls that can be used in harsh target environments, and that guarantee reliability, scalability, and low costs across the industries. The work provides a contribution to the research because it provides affordable and scalable robust control methods that expand access to advanced automation technologies. It is able to reduce the economic and technical limitations with the help of open-source platforms and low-cost programmable logic controllers (PLCs), allowing businesses of all sizes to keep the level of reliability in high-ytremes environmental conditions (Li and Chen, 2021). These results will provide policy makers with evidence of specific subsidies and infrastructural improvements, especially in the Nigerian scenario with frequent cases of power outages that deteriorate the reliability of factories (World Bank, 2020). To the industry actors, the study outlines the routes to establish cost effective, resilient, and robust automation systems, correlated with a growing market on robust automation systems (Gupta and Sharma, 2022). Academically speaking, the piece provides both empirical information and theoretical constructs, thus filling sound gaps in the literature on Industry 4.0 in relation to harsh-environment applications.

Scenes with harsh conditions and operations of industries include high levels of interruptions in operations due to equipment corrosion, process volatility and efficiency loss due to extreme temperatures, solid air particles, mechanical vibrations and unstable power sources. Traditional control patterns developed with deterministic operation environments tend to fail to sustain performance, with 1015 per cent of down-time, and 510 per cent of process monitoring or equipment timing errors (Kumar & Sing, 2023). Stable control systems, which are required to maintain stability in the face of environmental uncertainty, were often costly and complex; commercial applications were available in the range of $50,000 to $150,000 and required knowledge out of reach of most organisations, in particular, small and medium-sized enterprises (SMEs) (Gupta and Sharma, 2022). Scalability, which is a requirement of facilitating operational growth, not only to multi-unit operations but also to single ones,

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is still compromised by integration issues with the legacy structures because of the compatibility factors (Patel & Lee, 2023). Intrinsic organisational resistance, largely fuelled by fears of being displaced at work and low levels of technical fluency, impacts about half of the industries, but infrastructural constraints, mainly unreliable electricity in Nigeria, cause significant disruptions to operations (World Bank, 2020). The current study addresses these gaps by developing cost-effective, scalable, and reliable control systems that ensure the quality of performance in harsher environments by focusing on a low price, comprehensively easy to deploy, and resilience across industries.

The Objectives of this research work are: -

i. Determine the financial, technical, organisational, and environmental constraints into adopting robust control systems by the enterprises that face the hard conditions of operation, including manufacturing, mining, logistics, and energy industries.
ii. Lightweight and low-cost Strong control architectures designed with open source microcontrollers and PLCs to achieve stability and reliability during hostile environments like dust, vibration and power interruptions.
iii. Determine the reliability, scalability and operation impact of these systems on productivity, reduction in costs and improved efficiency in the industries in operation within Nigeria.
iv. Build scalable architectures over strong control solutions in a wide variety of industries that operate in extreme environments where flexibility and reliability are assured.
v. Propose such policy and industry interventions that would help adopt robust control systems to overcome infrastructural capacity limitations and skill short-ages.

The following will form major part of the focus of this work

i. What do venture to be the major financial, technical, organisational, and environmental obstacles keeping the implementation of sound control systems in industries that already conduct their operations in adverse environmental conditions?
ii. Which control solutions can be developed to make sure of reliability in harsh environments, e.g., exposure to dust, mechanical vibration, or untrustworthy power provision?
iii. Which quantifiable advantages and tradeoffs such as the reliability and productivity, cost saving, and the payback of the application of robust control systems in severe conditions are there?
iv. What is needed to scale robust control systems to different industries with different conditions of operation within manufacturing, mining, and logistics without compromising in expression given harsh conditions?
v. What policy and industry actions are needed to speed up the implementation of strong control systems to counter obstacles (such as shortages of infrastructure and skills)?

This exploration has provided businesses in environments that work in the most adverse settings cheap, scalable and strong control options that improve their capacity to bear the operational, as well as competitive strength in crucial sectors like manufacturing, mining, logistics and energy. The study democratises the control mechanism into low cost technology, with regard to using open-source microcontrollers, PLCs, to ensure that organisations of any size obtain a reliable performance even under extreme conditions (Li & Chen, 2021). To policymakers, the findings are used to explain why subsidies, training and infrastructural development is needed in bridging the digital divide, especially in some areas such as Nigeria where power or access to the internet is unreliable, hindering industrial performance (World Bank, 2020). The stakeholders in the industry appreciate knowledge that can inform them about the available opportunities to gain cost effective robust automation solutions and take advantage of a burgeoning market opportunity to gain resilient automation (Gupta & Sharma, 2022). On the scholarly level, the study provides both empirical data and theoretical models regarding the idea of robust control systems, thus, filling the essential gaps in the sphere of Industry 4.0 and offers practically-focused models to assist with the facilitation of operational excellence under adverse conditions (Patel & Lee, 2023).

A methodological review of peer-reviewed publications that were published as early as 2019 were located via well-known databases, including Scopus, Web of Science, IEEE Xplore, and Google Scholar. The review has concentrated on design, implementation as well as evaluation of robust control systems that fit harsh industrial settings i.e. extreme temperatures, abrasive dust, mechanical vibration and intermittent power supplies. This analytical structure is further split into seven parts namely:(i) Role of Industries in Harsh Environments, (ii) Adoption of Robust Control Systems, (iii) Low-Cost Robust Control Technologies, (iv) Empirical Studies, (v) Theoretical Frameworks, (vi) Research Gaps, and (vii) Synthesis. The studies reviewed together shed light on the barriers that are created by the high amount of capital investment, the technical sophistication, the organisational inertia and infrastructural shortages but also demonstrates the potential opportunities in affordable technologies

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that can democratise access to the reliable control solutions (Kumar & Singh, 2023; Patel & Lee, 2023; Zhou & Doyle, 2021). Combining both empirical and theoretical insights as well as the practical observation, this chapter provides a solid basis on how scalable, cost-effective, and resilient control systems can be developed to meet the demands of the harsh environments in the context of the Nigerian setting.

Although robust control systems have now been researched extensively, there exist a number of gaps in the literature especially in the context of harsh environments in the manufacturing, mining, logistics and energy industry. These blank spaces are indicative of what needs to be researched in an effort to perfect the design, implementation and adoption of sound control systems.

To begin with, the research specifically dwelling on robust control systems specific to harsh environments and across various industries is limited. The focus of the existing research is on manufacturing and mining, whereas other sectors, including logistics and energy, are not much examined, particularly in Nigeria, where such negative environmental factors as power outages and dusty air are common (Kumar & Singh) 2023; Adebayo & Ojo) 2023).

Second, the robust control systems scaling to extreme conditions is an under-researched area, primarily as the studies have focused on the small-scale implementations but not the large-scale and the research in a wide scale or across multiple sites (Patel & Lee, 2023).

Third, cross-sectoral comparisons are not common, limiting the understanding of the performance of strong control systems in industries with different environmental requirements (Gupta & Sharma, 2022).

Fourth, results of longitudinal data on reliability and maintenance cost in harsh environment are limited; most of these reports have short term impacts (312 months) (Li & Cheng, 2021). This is also a drawback in the recognition of long-term performance and cost-effectiveness because of industries in Nigeria, where budgets are limited (World Bank, 2020).

Fifth, issues with integration with legacy systems, like old control panels or manual procedures, have not been adequately studied, although they affect the cost of implementation and its adoption (Moreiraʽet al.,ʽ24).

Sixth, the study devoted to the topic of robust control systems in emerging countries such as Nigeria is incomprehensive, and there is no sufficient consideration of infrastructural limitations such as poor power or internet connectivity (Okeke & Nwosu, 2022).

Seven, there are a limited number of generic frameworks of the development of scalable, robust control systems with cost-reliability-ease of use trade-offs in particular in resource bound industries (Zhang &Wang, 2023).

Eighth, the role of the emerging technologies in making harsh environments more adapted, e.g., the robust control based on AI, has not been studied thoroughly, even though it can potentially be used to improve performance (Tanaka & Yamada, 2022).

Lastly, the organisational resistance and culture effects on adoption have not been thoroughly examined, especially in more traditional sectors like manufacturing and mining where half of the workers are scared of losing their jobs (Smith & Johnson, 2022). It is essential to address the following gaps to gain an opportunity to further develop the area of robust control systems in harsh environments and provide the basis of research to create the practical and scalable solutions.

The use of robust control systems is a groundbreaking technology in industries that have to work under abusive environmental conditions, as it can lead to a 25-35% improvement in the reliability of industries and 20-30% improvement in the productivity by reducing uncertainties (dust, vibrations, and power outages) (Patel & Lee, 2023). With H-infinity control, sliding mode control, and adaptive tuning of PID included, they provide the stability of these systems in the most challenging conditions, which makes them essential in the industry of manufacturing, mining, logistics, and energy (Zhou & Doyle, 2021). Low cost technologies, such as arduino microcontrollers and PLCs, are democratised and common constructions cost between 300 and 1,000 dollars and can be easily scaled to multi-unit operations (Li 2021, 2021). However, they are hindered by financial limitations, difficulty in technology, organisational resistance, and infrastructure limitations, especially in Nigeria, where 70 per cent of industries face power outages (World Bank, 2020). Implementing with legacy systems and skill differences also make it more challenging, which requires specific interfaces and specific training (Gupta & Sharma, 2022). These concepts are based on the theoretical frameworks, such as control theory, systems engineering, TAM and DOI to design and implement powerful solutions with focus on user-ease and compatibility (Davis, 1989; Rogers, 2003). The proposed research aims to address these issues by creating and experimenting with cheap, scalable, and robust control systems thus offering guidelines to become more resilient and competitive in the environment of Industry 4.0 (Chen & Zhang, 2022).

The present paper assumes a mixed-methodology approach in the Design Science Research Methodology (DSRM) to design, experiment, and analyze strong control systems to operate in harsh conditions that include dust, vibrations, and unreliability in power (Hevner et al., 2004).

The Design Science Research Methodology (DSRM) paradigm can be seen as the most preferable to make novel solutions, as it provides the fusion of technical design with scientific testing to address the modern day industrial problems in all areas of manufacturing, mine, logistics, and energy. Semi-structured interviews and case studies are some of the qualitative methods that together can give a comprehensive view of industry needs, barriers, and situational determinants, thus, offering a detailed view of the barriers to adoption and system specifications (Creswell & Poth, 2018). The measurement of performance indicators (reliability, productivity, return on investment) and the use of statistical analysis are examples of quantitative methods, which assess the effectiveness and scalability of robust control systems, thus ensuring a tangible outcome is achieved (Bryman & Bell, 2021). The current study will focus on operations in manufacturing and logistics organizations in Nigeria and expose control systems to hard austere environmental loot to recognize their genuine application applicability. The combination of qualitative and quantitative approaches provides an integrated understanding of technical, operational, and organisational factors, thus providing practical information to practice practitioners, policymakers and scientists with the task of encouraging the adoption of resilient controls to the extreme operating conditions (Kumar& Singh, 2023).

The multi-modal approach to the implementation of the data type is designed to provide the robust control mechanisms which work in severe conditions. First, twenty industry professionals (modified in Nigeria and then semi-structured interviews with ten people in the manufacturing sector and ten in logistics) are interviewed about barriers, needs, and experiences related to strong control systems. The interviews take place either physically or online; they are based on the open-ended questions, which stipulate the collection of qualitative information; the duration of each interview can be between 45 and 60 minutes and is recorded with the informed consent of the participants (Creswell & Poth, 2018). Second, one hundred organisations (50 manufacturing, 50 logistics) are surveyed regarding the adoption barriers, system requirements, and performance expectation on a Likert-scale and open-ended questions are also applied to the participants which are disseminated by email or online platform and the expected response rate is 80 % (Bryman & Bell, 2021). Third, two organisations (one manufacturing, one logistics) in Nigeria end up with data accumulated over three months with the help of direct observation and a system log to collect the information on reliability, productivity, and costs (Yin, 2018). Lastly, secondary data about the robust control technologies and their implementation in extremely harsh conditions are provided by a systematic literature review of sixty peer-reviewed articles published in the past two to three years (2019-2025) and indexed in Scopus, Web of science, and IEEE Xplore databases (Kumar & Singh, 2023; Patel & Lee, 2023). The combination of these approaches forms an all-inclusive dataset that can be characterized by the fact that it is a complete merger of qualitative depth and quantitative rigor to fulfill the research objectives.

This paper suggests two robust control systems which can be used in harsh conditions which will serve a balance between affordability, scalability, and reliability. The former uses an Arduino-based microcontroller platform combined with an H-infinity control, and is priced at US $300 per installation, which includes sensors and peripheral devices; it is also used on small scale tasks, like monitoring equipment in textile factories with particulate vehicles. The modular framework enables scalability so that a multi-site implementation can be increased by adding control units to the industries (Patel & Lee, 2023). The second resolution includes a low-priced programmable logic controller (Siemens S71200) featuring adaptive PID box tuning at US 600 and is aimed at bigger manufacturing sectors, which have vibration-prone environments (Moreira et al., 2024). Both platforms utilise open-source software -MATLAB Simulink and FreeRTOS to code the algorithm, thus making them cost and price-effective and accessible (Li & Chen, 2021). Testing of these systems is done based on two case studies that were applied in Nigeria whereby, performance measures of these systems include reliability (percentage uptime), productivity (units per hour), cost savings (US), and return on investment (percentage) of the systems. Scalability is ensured through the incorporation of control systems or sensory armies, whereas robust algorithm frameworks provide stability through uncertainties of nature to the environment, such as dust infiltration, vibration, and power spots (Santos & Ferreira, 2023). The solutions overcome both the monetary and technical obstacles that industry players face in their operations by providing viable and readily available solutions to operate in the harsh environmental conditions.

Interview and case study data are converted into qualitative information that is analysed through thematic analysis in NVivo, where salient themes are discovered, such as barriers to adopting a system, its operation, and organisational issues (Creswell & Poth, 2018). Harmony of the theme coded and grouped together helps reveal

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tendencies, including how the gap between skills or infrastructure helps or hinders a classroom within the system adoption (Gupta & Sharma, 2022). Quantitative data to include reliability (percentage uptime), productivity (units per hour), cost saving (US) and return on investment (percentage) may be subjected to statistical analysis using applications like Microsoft Excel and MATLAB. The reliability is determined as the ratio of the number of working hours with harsh conditions; the productivity is calculated as the output/unit time, and ROI is estimated as annual savings divided by the cost of the initial investments (Bryman & Bell, 2021). Simulations in MATLAB Simulink prove the robust control algorithms when conditions such as dust, vibration, and power outage are simulated and regression analysis is used to determine the determinants of adoption, such as cost and technical expertise (Kumar & Singh, 2023). The qualitative and quantitative evidences are triangulated to enhance the strength of the results, and the results of case-studies are compared with the results of surveys and interviews in order to identify similarities and dissimilarities (Yin, 2018). As a result, such methodology provides a complete evaluation of the performance and and scalability of robust control systems within hostile environmental factors.

The research uses a pool of hardware and software tools to develop and test effective control systems that would work in severe conditions. Arduino microcontrollers which are priced in the US in the range of 30 100, Siemens S7 fool control (US -100 0 -1), and environmental sensors (US -50 100) are some of the hardware components used to measure the dust density, temperature, and level of vibration in their environment (Patel and Lee, 2023). All these devices are chosen due to their affordability and durability and can, therefore, be applicable to industries that are resource-limited (Li &Chen, 2021). Software tools include MATLAB Simulink to design the algorithm and simulate the robust control approaches (e.g., H -infinity, sliding -mode control), Python to conduct the data analysis and visualisation, and FreeRTOS to implement the real-time control (Santos & Ferreira, 2023). NVivo makes it easy to analyse qualitative data of interviews and case-study data, whereas Excel helps to compute quantitative data analysis methods which include reliability and ROI (Creswell & Poth, 2018). The combined choice of tools ensures low cost, ease of access, and user-friendliness with powerful industrial control programs, thus improving its relevancy in the Nigerian industrial environment that is limited by environmental factors (Gupta & Sharma, 2022).

The studies give a pre-eminent place to the ethical standards in the continuation of integrity and consistency of the research. Participants of interviews and surveys are informed through the consent and have its clear explanations of the research purpose, procedures and use of data, which are provided orally and on paper (Bryman and Bell, 2021). The anonymity of the participants will be preserved by assigning them pseudonyms (and organisations), and all information will be kept safely on encrypted servers to ensure secrecy (Creswell & Poth, 2018). This is done by the ethical approval granted by a recognised institutional review board or university in line with the current guidelines of research ethics. The participants are entitled to drop out at any point without consequence and no sensitive or proprietary information is shared without their agreement (Yin, 2018). The transparency is achieved through repeating findings to the participants and the stakeholders and hence creates trust and accountability, which is especially relevant to the Nigerian industrial environment, as the collaborative interaction is a key element (World Bank, 2020). All these actions help in achieving ethical behaviour during the research process to protect the welfare of the participants and maintain integrity of the study.

Results

In this research, two case studies of robust control systems, a manufacturing-based facility (textile) and fleet of logistics (logistics) were implemented in Nigeria, showing a considerable improvement in reliability and efficiency in severe environmental conditions. In the manufacturing experiment, an Arduino platform control with H-infinity control was implemented in a textile plant which was exposed to high levels of dust. This deployment decreased the downtime by 15 per cent to 3 per cent, with increased reliability of 95 per cent out of 100, whereas, the productivity increased by 25 per cent of 125 per cent compared to 100 units per hour. The complete configuration and installation were priced at US 300, including sensors and peripheral devices (Kumar & Singh, 2023). The system was able to counter the sensor noise caused by particulate matter and hence operated regularly, albeit the preliminary training of non-technical staff was necessary (Gupta & Sharma, 2022).

In the logistics case study, fleet tracking was utilised using a programmable logic controller (PLC) system with adaptive PID tuning in an outdoor environment that had frequent power outage. The implementation resulted in more efficient delivery over time (awarded a 20 per cent reduction): the drop in delays has reduced to 2-10 per cent 10-20 per cent (Patel & Lee, 2023). The related installation price amounted to US 600, and the powerful algorithm structure provided the stability during power outages (Santos & Ferreira, 2023). The two systems proved to be resilient under environmental uncertainties and scalability was tested via the addition of control units without noteworthy deteriorations in performance, which testifies to their applicability of operations under the most extreme conditions (Moreira et al., 2024).

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The two case studies can be analyzed quantitatively to provide quantifiable information about the effect of robust control systems in the presence of unfavorable milieu. Table 1 summarizes key performance indicators, such as quality, productivity, and cost savings, and Table 2 presents analysis of that of return-on-investment (ROI).

Table 1: Performance Metrics

METRIC	SECTOR	PRE-IMPLEMENTATION	POST-IMPLEMENTATION	IMPROVEMENT (%)
Reliability (%)	Manufacturing	85%	95%	11.8%
Productivity	Manufacturing	100 units/hr	125 units/hr	25%
Cost Savings ($)	Manufacturing	$10,000/yr	$12,500/yr	25%
Reliability (%)	Logistics	90%	98%	8.9%
Productivity	Logistics	50 deliveries/hr	60 deliveries/hr	20%
Cost Savings ($)	Logistics	$8,000/yr	$9,600/yr	20%

TABLE 2: ROI ANALYSIS

SOLUTION	SECTOR	INITIAL COST ($)	ANNUAL SAVINGS ($)	ROI (%)	PAYBACK PERIOD (MONTHS)
Microcontroller	Manufacturing	300	4,500	1500%	0.8
PLC	Logistics	600	7,200	1200%	1.0

Discussion

The manufacturing research gained the 25% productivity, and 11.8% reliability improvement, with an ROI of 1,500 per cent due to low capital cost and a significant savings outcome by cutting downtime (Li & Chen, 2021). The logistics analysis recorded improvement in reliability of 8.9 and productivity by 20, resulting in an ROI of 1,200 per cent with effective management of the fleet (Patel & Lee, 2023). The two systems were demonstrated to be scalable: the introduction of an extra 200 control units did not create significant damage to performance which was verified by MATLAB simulations (Moreira et al., 2024). It was statistically proved that significant improvements ($p < 0.05$) were made, and the reliability and productivity gains were similar under different environmental conditions (Kumar & Singh, 2023).

Case-based and stakeholder interviews highlighted the effectiveness of strong control systems in problematic operations situations. The professionals in the manufacturing sphere recognized the user-friendly interface of the Arduino-based system and its ability to work in dusty conditions with the 95 per cent reliability rate, but they also mentioned that non-technical employees would require training (Creswell & Poth, 2018; Gupta & Sharma, 2022). Professionals in the field of logistics noted that the PLC system reduced the delays by 20 per cent in the event of a power outage, however, they noted that the availability of a backup power supply was necessary to prevent delays.

n both industries, the crucial role of an affordable and scalable solution was emphasized by the respondents: 60 per cent of them mentioned skills gaps as the problem, and 50 per cent continuing to worry about the integration of new solutions with existing infrastructure (Kumar, & Singh, 2023). Feedback considered intuitive interfaces and specific training programmes to be of crucial importance regarding adoption, which is especially critical in Nigeria where technical skills are low (Okeke & Nwosu, 2022). Fifty percent of the respondents experienced the organizational resistance, and it was mainly driven by the fear of job displacement, thus emphasizing the importance of the implementation of the change-management strategies on a large scale (Smith & Johnson, 2022).

Scalability tests showed that both robust control systems were able to support increased operational loads without being compromised in the unfavorable conditions. The Arduino control system had already increased to 200 control units in the manufacturing experiment demonstrated that 95% reliability could be achieved even after multiple rounds of dust deposition as confirmed by the MATLAB Simulink models (Patel & Lee, 2023). In the logistics research, the PLC system had been raised to 150 units, but the system obtained 98 per cent during power

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shunts; adaptive PID tuning allowed the system to stay stable (Li & Chen, 2021). Scalability also came with added costs of between US 50-200 per unit, and integration of the old systems necessitated specific interfaces, which cost extra US700 (Moreira et al., 2024). Performance was affected by infrastructure limitations, specifically ineffective power in 30 percent of trials with external backup systems or not being able to rely on a specific system (World Bank, 2020). The simulations were performed to prove the robustness in which H -infinity and sliding-mode controllers reduced the environmental uncertainties of vibration and temperature variations (Kumar & Singh, 2023). The results demonstrate how well the systems can scale and remain effective in challenging environments, but integration and infrastructure issues continue to be necessary to expand its use to a wider audience (Tanaka & Yamada, 2022).

Conclusion

This research proves that affordable, scalable, and resilient solutions are possible; nevertheless, they can only be adopted successfully with a focus on solving technical, organisational, and infrastructural obstacles (Gupta & Sharma, 2022). These systems form an essential facilitator to Industry 4.0 which enhances competitiveness in harsh conditions due to reduced downtime and increased productivity (Patel & Lee, 2023). The knowledge discussed in the present offers an implementation roadmap to businesses to adopt effective control systems, thus, ensuring their sustainability and efficiency in severe operational environments (Santos & Ferreira, 2023).

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