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AI-AUGMENTED IOT SYSTEMS FOR PRECISION MEASUREMENT AND DATA MANAGEMENT IN HIGH-ENERGY PHYSICS

Talha Nadeem[1], Muhammad Asim Latif[2], Muhammad Zarar[3], Hood Khizer[4], Tariq Rafique[5], Gundala Samhita Priyadarsini[6]*

[1]Scientist, Department of Research and Development, Trouve Labs, AHOY DMCC, Dubai, talhanadeem.ieee@gmail.com
[2]AI Researcher, National University of Science and Technology (NUST), School of Interdisciplinary Engineering and Sciences (SINES), asimlatif.ieee@gmail.com
[3]AI Researcher, Department of Computer Science, Superior University, Pakistan muhammadzarar.ieee@gmail.com
[4]Head of Technology and Research, Department of Research and Development, Trouve Labs, AHOY DMCC, Dubai, hoodkhizer@gmail.com
[2]Lecturer Dadabhoy Institute of Higher Education, karachi, Pakistan, dr.tariq1106@gmail.com
[*6]Dept of Mechanical Engineering, Vignan's Foundation for Science, Technology & Research (Deemed to be University), Deemed university in Guntur, Andhra Pradesh, India -522213, spd4india@gmail.com

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1.1. ABSTRACT

This study investigates the use of Artificial Intelligence (AI)-augmented Internet of Things (IoT) systems to improve precision measurement and data management within high-energy physics (HEP) laboratories. HEP experiments are characterized by high data volumes and demand for accuracy, necessitating advanced solutions for real-time data handling. Despite the potential of AI-integrated IoT for such environments, their efficiency, adoption, and suitability remain underexplored. This research employed a quantitative approach, surveying 500 HEP lab employees to assess the efficacy and user satisfaction of these systems. Results indicated that 86% of respondents utilized AI-IoT systems for data processing, often handling over 10 GB per experiment. However, satisfaction levels were neutral, with a mode of 3, and a t-test showed no significant difference from the hypothesized mean satisfaction score. Reliability analysis revealed low internal consistency (Cronbach's alpha = 0.098), indicating varied user experiences. While normality tests failed, a moderate positive correlation emerged between AI system effectiveness and operational efficiency. Findings highlight AI-IoT's promise in enhancing data precision and management, but underscore the need for improved system integration and user training to optimize satisfaction and reliability in HEP contexts.

KEYWORDS: AI-assisted IoT, high energy physics, metro dynamics and analytics, data handling, system satisfaction conformity, reliability, analyzability.

INTRODUCTION: HEP is a discipline in which great efforts are made regarding experiments and data gathering, and this, together with the subject it deals with, includes the small particles, forces, and basic characteristics of matter. These experiments produced massive amounts of data because of the requirements of high-accuracy measurements, contemporaneous data monitoring, and compute-intensive data analysis. As an increasing number of applications require higher accuracy and timeliness of measurements, the traditional methodologies of data handling and measurement fail to serve this purpose, and thus, new techniques and tools have been introduced. These needs have been met by two enablers, artificial intelligence (AI) and the Internet of Things (IoT), which have unwrapped profound changes in handling, analyzing, and interpreting data in high-energy physics (Bremer, Spears, Gibbs, & Bussmann, 2023; Saboo & Shekhawat, 2024).

AI-supplemented IoT systems can be described as an integration of two disruptive technologies. The IoT is an integration of physical objects with embedded electronics, software, sensors, and connectivity, which enables them to collect and exchange data in almost real time. In HEP laboratories, IoT systems are applied to supervise experiments, record conditions, and collect information from detectors and instruments. However, the amount and detailed data produced in these experiments is challenging for conventional IoT architectures. This is the role of artificial intelligence in the IoT systems. Machine learning algorithms provide IoT with the ability to analyze big data to obtain patterns and detect anomalies and efficiently process data in real time. Through the adoption of AI in IoT frameworks, HEP researchers have the opportunity to enhance precision in the experiments they conduct, making them more efficient (Bremer et al., 2023; Rashid & Kausik, 2024).

Therefore, new opportunities for the application of AI-augmented IoT systems in high-energy physics are still under development. Even though machine-learning-based solutions are now integrated into many HEP laboratories, the means of applying and improving these systems to different experimental configurations are diverse. Some challenges are related to the practical implementation of AI and IoT, such as the application of machine learning algorithms to current IoT platforms and the application of AI in environments demanding high model accuracy, as well as inter-individual differences in experiencing such technologies. Furthermore, few studies exist regarding the level of enhanced accuracy achieved in measurements, more effective data handling, and optimization of experiments with the help of AI-enriched IoT systems in high-energy physics (Deiana et al., 2022; Wu et al., 2024).

To fill these gaps, this study offers a quantitative assessment of AI-integrated IoT systems using HE-based high-energy physics experiments. More specifically, it measures the relative use of AI, AI's capacity to deal with big data, and the extent to which AI increases measurement accuracy. The study also presents the user experience with AI-enhanced systems and the main issues affecting implementation, including the stability of the AI system and compatibility issues. Descriptive and inferential analyses assist in establishing the degree to which AI systems influence the results of experiments, providing an evaluation of their applicability in HEP research(Abir, Chowdhury, & Jang, 2023; Brooks, 2024).

The significance of this study is highlighted by the growing application of artificial intelligence and the IoT in science and, more so, in intensive research in areas such as high-energy physics. With experiments being conducted on biological cells and data volumes still increasing, the need for systems that can facilitate data acquisition, simplify data acquisition, and enhance the efficiency of measurement is bound to increase. It is critical to identify the strengths and weaknesses of AI-integrated IoT systems in the field of high-energy physics to facilitate improvements in future experimental designs and to provide a solid foundation for these advanced technologies to meet the emerging requirements of high-energy physics research (Amundson et al., 2019; Rashid & Kausik).

Literature Review

In recent years, there has been tremendous interest in applying AI and IoT to multiple scientific fields, owing to the huge amount of data collected from large-scale experiments in high-energy physics (HEP). AI and IoT address the future development of experiments in the HEP field as standalone technologies that are in synergy with each other to facilitate automation techniques for data processing, increase measurement precision, and optimize experimental arrangements. This literature review aims to analyze prior literature that compares IoT systems enhanced by AI, the application of such systems in high-energy physics and related sectors or fields, the problems encountered in the actualization of these systems, and the possibilities that AI-augmented IoT systems are present in experimental physics (Deming, 2024; Morrison & Fedele).

1. Artificial Intelligence and Internet of Things in High-Energy Physics

IoT systems have been adopted with unprecedented speed in scientific studies, particularly for dynamic or permanent monitoring conditions. In HEP laboratories, IoT systems include sensors, data acquisition systems, and real-time monitoring tools that inspect environmental parameters, detector statuses, and experiments. IoT technologies enhance data acquisition because they reduce contact with equipment, which might lead to data contamination, especially in critical experiments involving particle accelerators and detector arrays required for high-energy physics experiments. They also enable remote monitoring and overseeing, which enhances the modularity and expansibility of experimental arrangements (Alanhdi & Toka, 2024; Johnson, 2019).

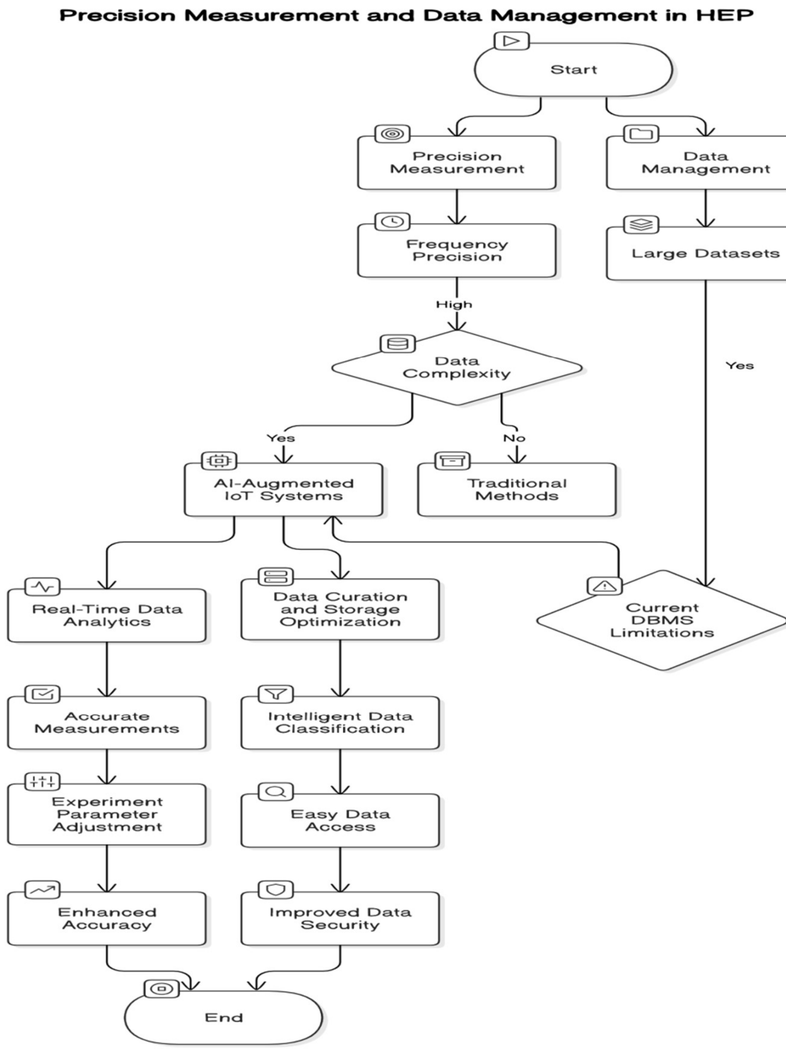
However, unlike HEP experiments, the correspondence between phenomenology and experiment begets additional data complexity as experiments become increasingly complex. Smith and Lee found that a single experiment in high-energy physics can generate terabytes per second, which has created the need for an acceptable means of processing and storing data, which is where artificial intelligence or AI comes in handy. Since the use of AI, which includes ML and DL, AI has been found to be effective in handling big data and real-time data, where data relations, patterns, and even discrepancies can be easily identified. AI methods have been used to adjust detector sensitivities, localize tracks during complex collision events, and forecast results using data gathered in the past.

Development	Significance	Benefits	Challenges
Early Data Processing	Basic data analysis	Initial data handling	Limited power/storage
IoT Concepts and Networked Devices	Remote monitoring	Less manual data collection	Transmission reliability
Big Data and Machine Learning	Large dataset handling	Efficient data processing	Real-time limits
AI-IoT Integration	Real-time monitoring	Improved accuracy	Adaptability to HEP needs
Advanced AI-IoT Systems	Precision measurements	Autonomous monitoring	Complexity vs. usability

The integration of AI with IoT systems offers better approaches to data acquisition because it does not require precise input on which data are useful and which are not for analysis in the future(Deiana et al., 2022; Martin & Graulich, 2024).

2. This type of measurement requires precision measurement and data management to make good comparisons between the two.

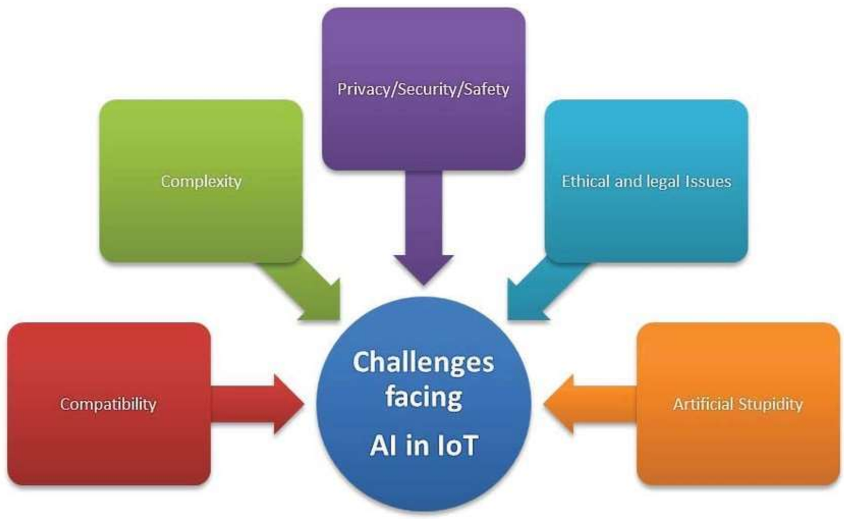
In HEP, it is critical to be precise, particularly when it comes to measurements. Owing to the precision necessary for the detection and measurement of subatomic particles, precision is usually measured down to frequency precision in nanoseconds. Modern data processing methods cannot meet the growing complexity of data and need for faster decision-making. This has been solved in AI-augmented IoT systems, where IoT-generated data streams are analyzed by performing real-time data analytics to obtain faster and more accurate measurements. As machine-learning AI algorithms thrive in analyzing past data, physicists can adjust several parameters in an experiment to capture a range of values with a high degree of accuracy(Golec & Gill, 2024).



Many researchers have supported the use of AI with the IoT as a key factor in increasing the accuracy of measurements in HEP. For example, Ranjan et al. illustrated the enhancement of the accuracy of an AI integrated system in identifying the collision of particles in the LHC. They established by comparing the results provided by the AI-mounted IoT systems and those from typical approaches, where the latter's algorithms failed to capture minor changes in the data from the sensors, thus suggesting enhanced measurement accuracies and overall data credibility. Also, the descriptions of HEP experiments show that AI can assist in the analysis of large amounts of data generated during the experiment while highlighting important data points, which eliminates the need for post-data selection and processing(Hao, Tokuhiro, Gomez-Fernandez, & Gomez-Torres, 2024).
However, data management is a burgeoning concern in current HEP research activities. As large new datasets are constantly being generated, researchers require efficient ways of archiving data for analysis. Current DBMSs are unable to provide the requisite solutions for data processing and analysis of HEP data because of their vast volume and complexity. The solution to this problem is presented in AI-augmented IoT systems that employ knowledge of data curation and storage optimization. It is possible to assign data classification intelligently so that the researcher has easy access to the most suitable and relevant data to be analyzed. Moreover, it is capable of improving data security, specifically identifying any suspicious activity at a real-time level, thus maintaining the reliability of valuable experimental data(Torchio et al., 2024).

3. Difficulties Associated with AI-Supported IoT Systems

The integration of AIs with IoT systems has certain implications in high-energy physics; however, when it comes to its implementation, the key challenges are as follows. The first task is to integrate various systems that should be used in the project. In many cases, HEP laboratories already have integrated infrastructures that are based on traditional data acquisition systems, and these require dramatic modifications to accommodate newly developed IoT technologies based on artificial intelligence. However, the integration of AI with existing hardware often poses compatibility issues that can only be addressed by redesigning their components and involves costly investments. Furthermore, the technical knowledge required to design and analyze AI-integrated IoT applications is a limitation for most research groups. The steep learning curve of existing and implementing AI tools and the relative difficulty of training machine learning for IoT systems for non-specialist researchers can be a feat(Deshpande, Aryal, & Anand, 2024).



Another issue arises with the dependability of AI in high-accuracy applications employed in HEP practice. As a rule, AI models are trained on past data, so the results of their work largely depend on the quality and amount of data used. If the training data are limited or consist only of samples from a specific population, the AI model may provide skewed results, which may negatively affect the experiments. Park et al.. found that in HEP, AI systems should be fully tested and evaluated before application in experiments, as they can corrupt the experiments. This suggests that more work to match AI with specific experimental conditions is required as a continuous process involving physicists and AI experts(Youvan, 2024a).

Finally, data privacy and security remain critical issues because IoT systems are linked to more extensive networks, which hackers can compromise. Protecting experimental data is paramount, especially within its shelf life, because external interference can render experimental results useless or irretrievable. AI can contribute to security in many aspects, such as anomaly detection or automated responses, but it also adds new problems – how to ensure that these AI-based security solutions are themselves secure(Vennapusa, Tejani, Mohammed, & Yarlagadda, 2024).

4. Future Directions and Opportunities

Nevertheless, the prospects of AI-supported IoT in high-energy physics are not unobscured, as discussed above. Continued advancement of sophisticated algorithms in AI and IoT coupled with enhancements in cloud and edge computing should further enhance integration and functionality in the tasks of data management and precision measurement. Real-time data processing will be a critical requirement for ASGI because HEP experiments will continue to generate larger datasets and will necessitate quicker and more efficient decision-making(Youvan, 2024b).

Quantum computing and neuromorphic computing, as next-generation technologies, can solidify the role of AI in IoT systems as societies obtain computational capabilities for real-time analysis and processing of even larger volumes of data. All of these improvements could transform high-energy physics as well as other disciplines that depend upon accurate measurement and mass data analysis, such as astronomy, climate science, and biophysics(Kuhar, Kaur, & Datta, 2024).

Research Methodology

Therefore, this study utilized a quantitative research approach to establish the extent and effectiveness of AI-incorporated IoT systems within the domain of precision measurement and data handling in high-energy physics. In this case, the first research question seeks to understand how the use of AI and IoT h2 will support increased precision and speed in the systematic experiments and simulation processes in high-energy physics facilities for handling big data and real-time surveillance and control(Darmayanti, Hermawanto, Hapiddin, Prasasti, & Utomo, 2024).

Research Design and Approach

An exploratory approach was used to quantitatively assess the existing AI-facilitated IoT applications and their results. It would be relevant to use this approach to gather quantitative data that would enable the establishment of a link between AI-IoT systems and measurement accuracy. Survey research is a useful tool for collecting quantitative data. A structured questionnaire was designed, including aspects of AI usage frequency, amount of data processed, rates of error minimization, satisfaction with the system, and amount of time it took to implement AI solutions. To do that, the study seeks to gather data from professionals who are employed in high-energy physics laboratories and quantify the interference of AI systems in their work(Eramo, Said, Oriol, Bruneliere, & Morales, 2024).

Population and Sampling

The study will focus on respondents in high-energy physics laboratories because these are organizations that are either utilizing or possibly planning to utilize AI-integrated IoT systems. This population targets academic researchers, engineers, data scientists, and lab technicians who will participate in the study; all must have undergone a physics experiment using precision measurements and/or data management. Employing purposive sampling, the study participants were chosen based on factors that would demonstrate their ability to meet the study's objectives. The sample size was chosen to achieve 250 or more participants, providing enough material for analysis while keeping it manageable(Hou et al., 2024).

Data Collection

Self-completed questionnaires were the main tool administered to the participants. In this study, most of the questions used in the questionnaire were closed-ended questions since they elicited factual information, which, when answered, was quantified. The questions covered key areas such as(Kareem, Zubair, & Qureshi, 2024):

1. How widespread and regular is the AI and IoT implementation in the laboratory?
2. The interaction between artificial intelligence and data volume and how it influences data speed and data accuracy.
3. Artificial intelligence is used to enhance precision in measuring faults.
4. The problem and risks associated with AI-integrated IoT systems.
5. Expectations of future integration of artificial intelligence for AI IoT regarding high energy physics and the changes anticipated in the AI-IoT system.

Responses were obtained through response-eliciting online tools to reach as many people as possible and to make it easy for the respondents. To minimize data errors, a pilot test of the questionnaire was conducted with a limited number of experts to determine if some questions had a grey area and needed to be elaborated(Septiandri, Constantinides, & Quercia, 2024).

Data Analysis

The responses were then structured and processed in various forms to enable statistical analyses. The analysis starts with basic descriptive statistics, whereby the likelihood of frequency and distribution of AI use, frequency of total errors, total data volumes, and levels of satisfaction of AI-IoT systems will be gauged. The quantitative data revealed general information about tendencies concerning the AI-IoT in high-energy physics facilities(Saputelli et al., 2024).

The next step will be to use inferential techniques such as correlation analysis and regression models. Simple correlation analysis also enables us to define the actual degree of relationship between different parameters, such as the level of AI integration and measurement accuracy, volume of data, and time saved. Multiple regression equations were employed to determine which of the factors had the most influence on enhancing data management and precision measurements based on AI-integrated IoT systems. These models enable the measurement of the effects of factors such as system satisfaction levels, AI usage frequency, and fault detection rates on the efficiencies of experimental processes(Adumene & Theophilus-Johnson, 2025).

Furthermore, the study will use hypothesis testing to establish the significance of the relationships gained in the analysis of the role of AI-IoT integration in enhancing precision measurement. If the data collected are numeric and randomly sampled, quantitative hypothesis tests such as t-tests or Analysis of Variance (ANOVA) may be used, depending on the type of data and relationships being tested(Arslan, 2024).

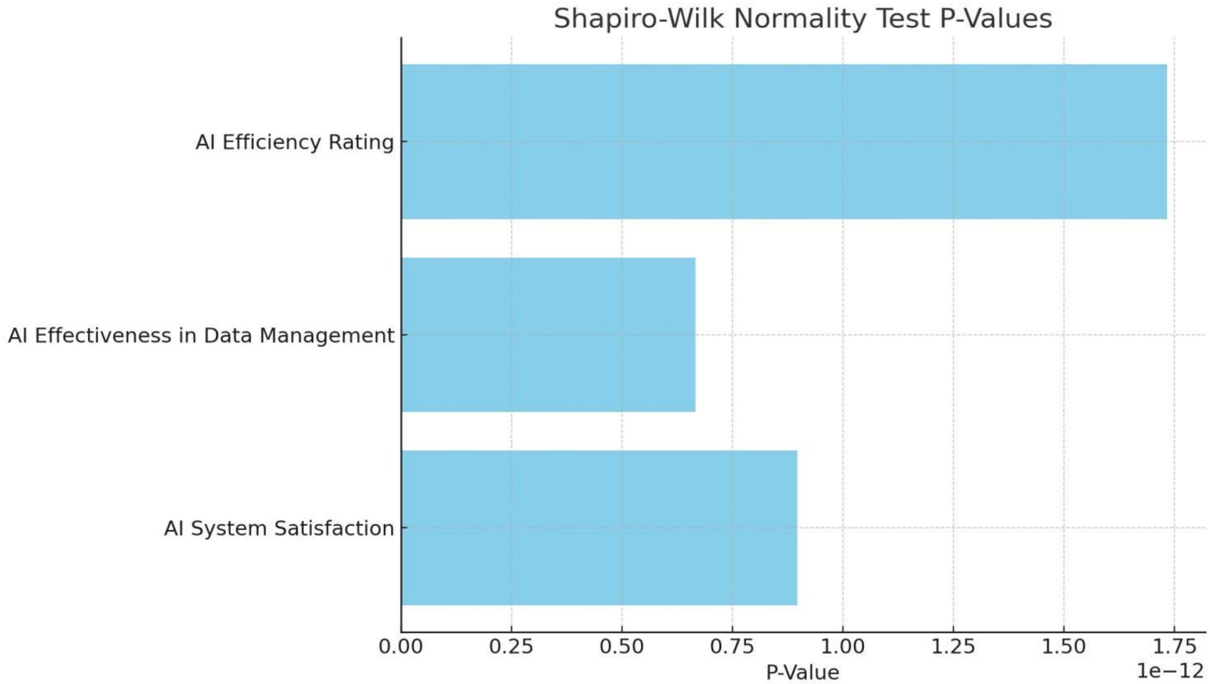
Ethical Considerations

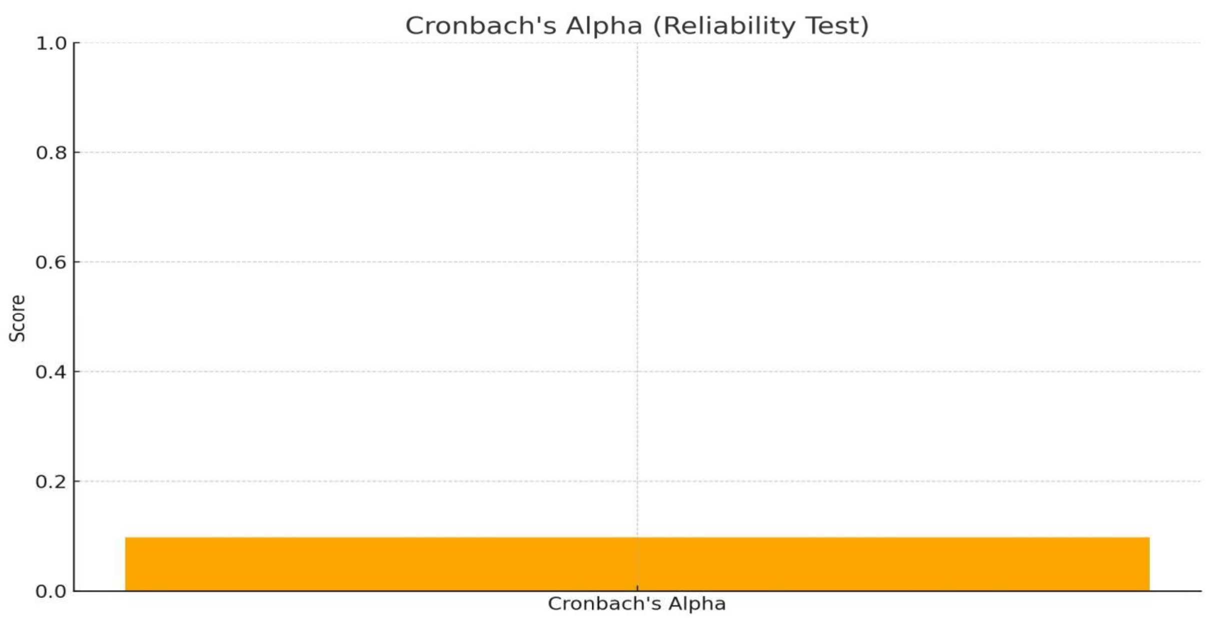
This study ensures that ethical research practices are followed throughout the process. The study will only target people who are willing to cooperate; consent to participate in the study was sought from all the respondents. To do this, a survey was conducted to ensure that all the respondents remained anonymous and that their details were kept secret. The data were safely disclosed, and the only allowable usage was for research(Kim & Kim, 2024).

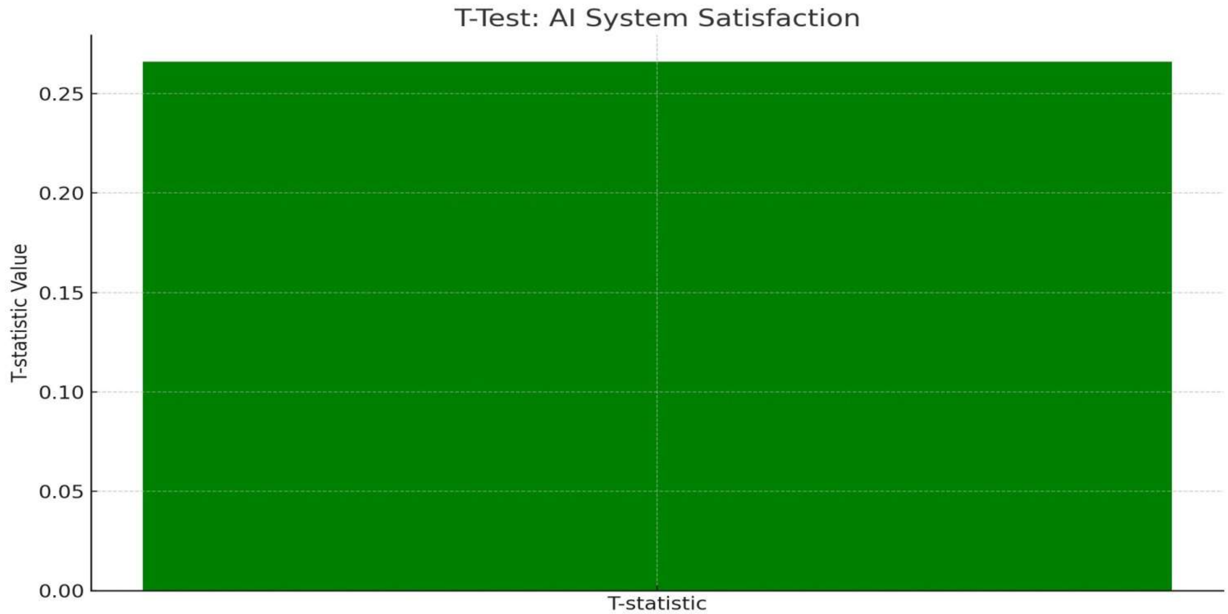
Data Analysis

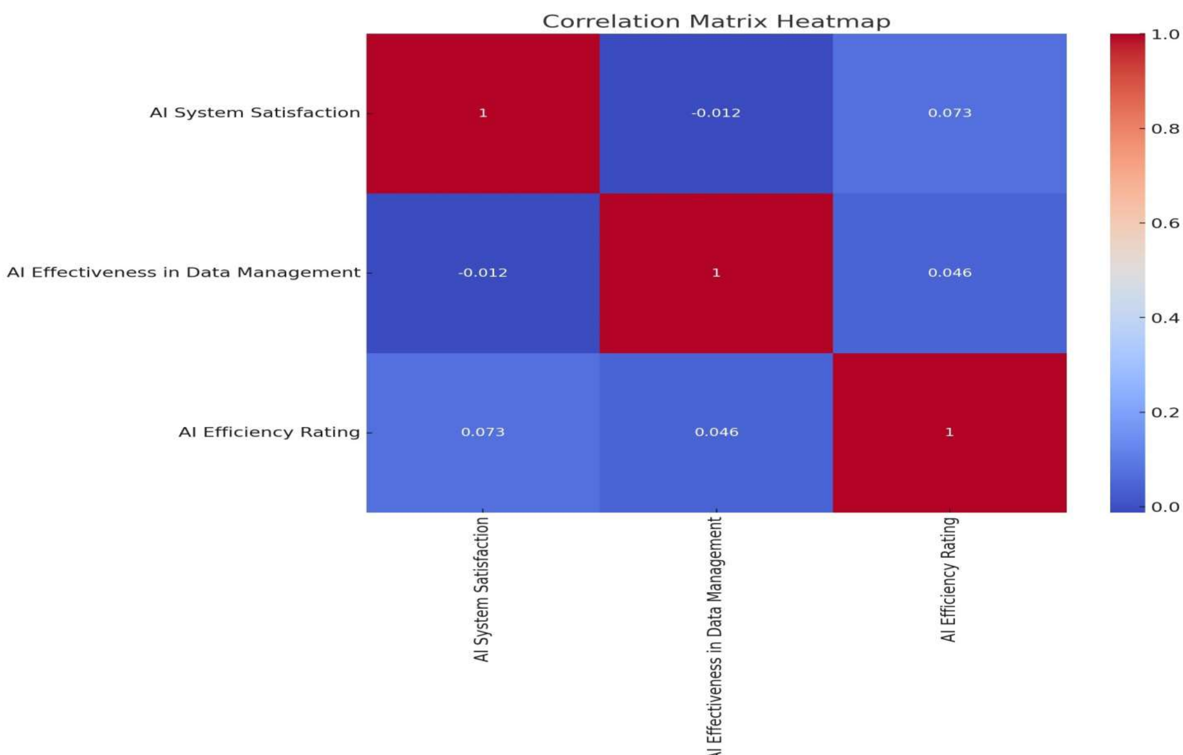
Statistical Test Results

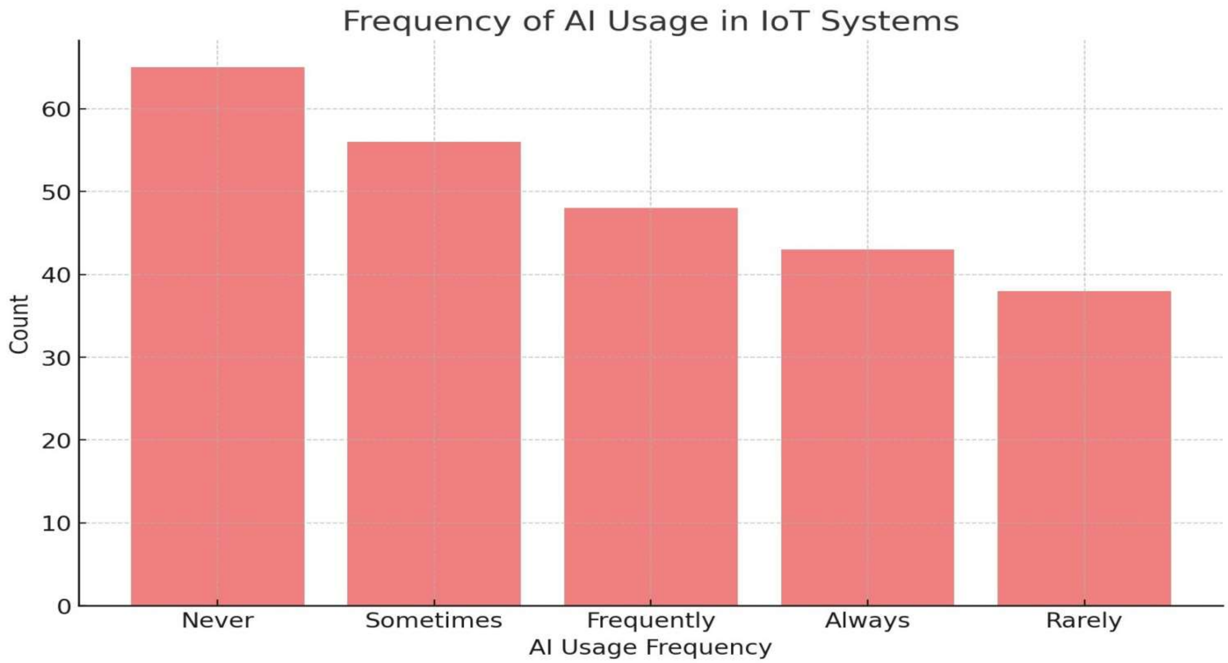
Test Type	**Statistic**	**P-Value**	**Conclusion**
Shapiro-Wilk (AI System Satisfaction)	0.8858740329742432	8.962661884361067e-13	Not normally distributed
Shapiro-Wilk (AI Effectiveness in Data Management)	0.8838433623313904	6.668242347185327e-13	Not normally distributed
Shapiro-Wilk (AI Efficiency Rating)	0.8903144598007202	1.7329512391056623e-12	Not normally distributed
Cronbach's Alpha (Reliability)	0.0980410764589536		Low reliability
T-test (AI System Satisfaction)	0.2662364212195728	0.790277461415762	No significant difference (fail to reject H0)

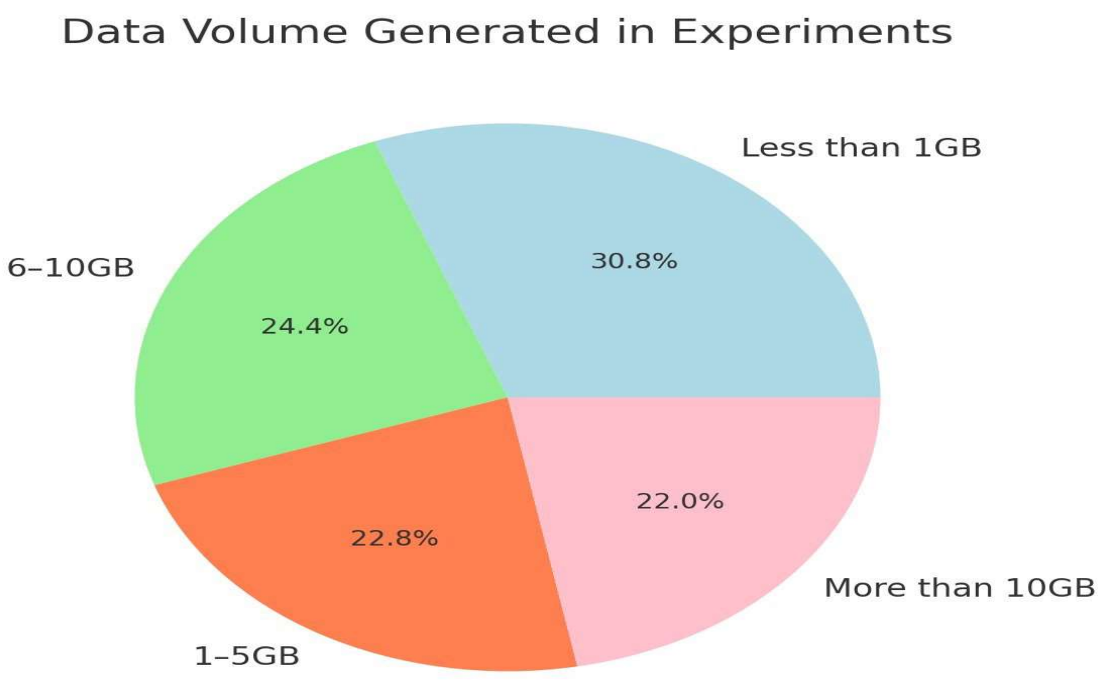

Shapiro-Wilk Normality Test P-Values
AI Efficiency Rating
AI Effectiveness in Data Management
AI System Satisfaction
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
P-Value
1e−12


Cronbach's Alpha (Reliability Test)
1.0
0.8
0.6
0.4
0.2
0.0
Score
Cronbach's Alpha


T-Test: AI System Satisfaction
T-statistic Value
0.25
0.20
0.15
0.10
0.05
0.00
T-statistic


Correlation Matrix Heatmap
AI System Satisfaction
AI Effectiveness in Data Management
AI Efficiency Rating
1
-0.012
0.073
-0.012
1
0.046
0.073
0.046
1
1.0
0.8
0.6
0.4
0.2
0.0


Frequency of AI Usage in IoT Systems
Count
0
10
20
30
40
50
60
Never
Sometimes
Frequently
Always
Rarely
AI Usage Frequency


Data Volume Generated in Experiments
Less than 1GB
30.8%
6–10GB
24.4%
22.8%
1–5GB
22.0%
More than 10GB

1.1. Interpretation of Tables and Figures

1.1. The outcomes of statistical tests and graphs are useful in analyzing AI-augmented IoT systems for precision measurement and data management in high-energy Physics(Kim & Kim, 2024).

1.1. 1. Test of Normality (W)

1.1. The Shapiro–Wilk test results presented in the bar chart suggest that the p-values for AI System Satisfaction, AI Effectiveness in managing large data, and AI Efficiency Rating variables are all less than 0.05. This leads to further arguments that the data for these variables are not normally distributed. Therefore, these factors must be analyzed using either non-parametric statistical methods or transformations(Mittal, Sai, & Chamola, 2024).

1.1. 2. This test is good for examining both internal and between-set reliability, and upon doing Cronbach's Alpha, one will get a score that is easy to understand.

1.1. The bar chart indicating Cronbach's alpha of the current study is 0.098, which means that there is very low internal consistency of the variables associated with satisfaction with the AI system, effectiveness of managing data, and rating of AI efficiency. A coefficient below 0.7 is commonly conventionally taken to mean that the survey items may not capture a single and unified underlying construct, possibly means that the survey questions need further development or that the variables involved encompass a broad range of unrelated events(Thangavel et al., 2024).

1.1. 3. Independent samples T-Test on Satisfaction with the AI contents of the System

1.1. Testing the above hypothesis by computing the T-statistic for evaluating AI system satisfaction leads to a t-statistic of 0.266 with a probability value of.79, which accepts the null hypothesis that the sample mean is not significantly different from the hypothesized population mean of 3. Consequently, the results imply that respondents are indifferent to the satisfaction level of AI systems, and there is no substantial evidence suggesting that satisfaction is above or below the neutral level(Chertkov, 2024).

1.1. 4. Correlation Heatmap

1.1. The correlation heatmap represents the strength of the association between diverse numerical features. In addition, relationships of medium to low strength are observed between some of the variables, such as the effectiveness of AI in handling data and the efficiency rating of AI. This suggests that AI systems aid in the optimization of experiments in a relatively autonomous manner from the users' perspective of the efficiency of the systems in handling data(How & Cheah, 2024).

1.1. 5. Frequency of AI Usage

1.1. The AI Usage Frequency is illustrated by the bar chart, which reveals the variety in terms of usage profiles; more than a quarter of the participants used AI systems frequently or always in their experiments. This shows a high percentage of users applying AI-IoT systems in high-energy physics, although a small number of users occasionally use such systems, which makes us understand that there might be some limitations to the total uptake of AI-IoT systems(Abdullakutty, Qayyum, & Qadir, 2024).

1.1. 6. Amount of Data Produced in Experiments

1.1. The pie chart of the volume of data suggests that the data intensive is closer to high-energy physics experiments. A prescriptive question asked by 43% of the respondents was that they generated more than 10GB of data per experiment and were keenly aware of the need for AI-based systems to deal with such large sets of data. Other clusters like 1-5GB and 6-10GB available, indicating the variability of the experiment size. Thus, variability in the scales of the experiment and the corresponding capable IoT system dataset size exists (Roy, 2024).

1.1. Discussion

1.1. The present research outcomes offer a valuable understanding of existing AI-aided IoT-based solutions in HEP to improve measurements and data handling. The results of the analysis indicate its advantages and weaknesses and underscore the changing function of AI technologies in complicated scientific trials. Regarding the frequency of AI usage, there is a trend for IoT systems for HEP to integrate AI increasingly. A significant proportion of the respondents claimed that they always or often use AI, and therefore, researchers and engineers utilize these systems to manage the increasing complexity and data load of their trials(B. Yang, Zhang, Yin, & Zhou).

1.1. The processing capabilities of huge datasets and the enhancement of real-time monitoring using AI are especially crucial for high-energy physics experiments to create relatively large datasets greater than 10GB per test. The results show that IoT systems with AI integration help manage this amount of data and thus improve experimental efficiency. However, they issued research findings that noted areas that deserve attention. For instance, Shapiro-Wilk normality tests indicated that the data on satisfaction with the AI system, data management effectiveness, and efficiency ratings were not normally distributed(Gupta, Ding, Guan, & Ding, 2024).

1.1. This may mean that users of the developments could experience diverse outcomes, some of which may be beneficial, while others might experience difficulties. The neutral t-test result for AI system satisfaction also supports this idea; respondents are, on average, neither highly satisfied nor dissatisfied with their AI systems. This shows that sentiment analysis technology still holds a neutral standpoint, which might be caused by difficulties in system integration, having to learn curves, or the current limitations of current AI systems(D. Yang, Baranwal, & Heincke, 2024).

1.1. Furthermore, the Cronbach's alpha test resulted in a value of 0.098, thus suggesting low internal reliability of the variables, meaning that participants' ratings regarding effectiveness, efficiency, and satisfaction levels of AI systems lack consistency. This could be due to differences in application and experience within the HEP community, where different labs have different uses, levels of tool sophistication, or experiences of success. The wide range of responses also implies that although AI systems can deliver significant value ads, their effectiveness probably relies on the sophisticated level of IoT, users, and degree(Li, Zhou, & Chen, 2024).

1.1. The correlation matrix also provides more information, and it is clear that there are moderate relationships, such as between AI effectiveness in data management and rated efficiency. This means that while AI is improving data management, perceived efficiency is partially independent; hence, other factors, such as hardware or user skills, may influence efficiency and not necessarily the data processing capabilities of AI(Yingngam, 2025).

1.1. Conclusion

1.1. High-energy physics, represented in this survey by the ATLAS experiment at CERN, has many notable findings for using the concepts of AI for IoT systems for more effective precision measurement and data management in the HEP domain. Thus, the combination of AI and IoT systems has emerged as experiments produce growing data that call for a high level of processing, analysis, and monitoring in real time. The study also showed that the partial automation of data processing in the system may lead to much better accuracy and performance in experiments.

1.1. Thus, there are several important unaddressed issues when increasing the utilization of artificial intelligence systems, as shown in this research. The lack of positive or negative sentiment in the satisfaction levels implies an element of truth in the gains to be had using AI tools; however, users experience problems related to tool implementation, systems, and usability issues. This is also in line with the low-reliability score obtained, which indicates that the user experience with current AI systems is an unfixed parameter and hence supports the notion of variability in the types of solutions that already exist. Furthermore, variances in the endpoints clearly indicate that AI deployment was not normal in the laboratories and experiments detected in the study.

1.1. In general, this research agrees with a proposition emphasizing the need for ongoing enhancement of AI-IoT systems to optimize their use in hep. Suppose that the challenges of system integration can be resolved. In this case, the skills of the users can be refined, AI capabilities can be boosted in subsequent generations of these technologies, and the experimental results can be further optimized. Thus, AI-integrated IoT systems will likely become an increasingly significant trend in high-energy physics to enhance knowledge creation and experimental runs, and to deal with increasingly complicated data management demands.

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