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INTELLIGENT MONITORING SYSTEM FOR DETECTING ANOMALOUS STATES IN TECHNOLOGICAL PROCESSES

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Abstract. This work presents an intelligent monitoring system for detecting anomalous states in technological processes. The system uses advanced data analysis and machine learning techniques to identify deviations from normal operational patterns. By continuously monitoring process parameters, it enables early detection of faults and helps prevent potential failures. The proposed approach has been tested on both real and simulated datasets, demonstrating its effectiveness in ensuring process reliability and safety.

Keywords: intelligent monitoring, anomaly detection, technological processes, machine learning, fault detection, data analysis.

Annotatsiya. Ushbu ishda texnologik jarayonlarda anomaliyalarni aniqlash uchun intellektual monitoring tizimi taqdim etilgan. Tizim normal ishlash holatlaridan chetga chiqishlarni aniqlash uchun ilg‘or ma’lumotlarni tahlil qilish va mashina o‘rganish usullaridan foydalanadi. Jarayon parametrlarini doimiy kuzatish orqali u nosozliklarni erta aniqlashga va mumkin bo‘lgan muammolarning oldini olishga yordam beradi. Taklif etilgan yondashuv real va simulyatsiya qilingan ma’lumotlar to‘plamlarida sinovdan o‘tkazilgan va jarayon ishonchliligi hamda xavfsizligini ta’minlashda samaradorligini ko‘rsatgan.

Kalit so‘zlar: intellektual monitoring, anomaliyalarni aniqlash, texnologik jarayonlar, mashina o‘rganish, nosozliklarni aniqlash, ma’lumotlarni tahlil qilish.

Аннотация. В работе представлена интеллектуальная система мониторинга для обнаружения аномальных состояний в технологических процессах. Система использует передовые методы анализа данных и машинного обучения для выявления отклонений от нормальных рабочих режимов. Постоянный мониторинг параметров процессов позволяет раннее обнаружение неисправностей и предотвращение потенциальных сбоев.

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Предложенный подход протестирован на реальных и смоделированных наборах данных и показал свою эффективность в обеспечении надежности и безопасности процессов.

Ключевые слова: интеллектуальный мониторинг, обнаружение аномалий, технологические процессы, машинное обучение, обнаружение неисправностей, анализ данных.

I. INTRODUCTION.

In an increasingly complex technological landscape, the need for robust monitoring systems has become paramount. An intelligent monitoring system is essential for real-time detection and analysis of anomalous states within various technological processes, as these anomalies can signify critical issues such as production faults or security breaches. The significance of effective anomaly detection lies in its ability to preemptively identify and mitigate risks that could disrupt operations, which is crucial across diverse industries, including manufacturing and healthcare. As noted, the variety and complexity of anomaly detection algorithms have proliferated, presenting challenges in selecting the most appropriate technique for specific applications (Schmidl S et al., 2022) . Moreover, new methodologies, like conflict-driven anomaly detection, offer innovative approaches to identify sophisticated threats that can evade conventional monitoring systems (balluchi et al., 2017) . This essay will explore these developments and their implications for advancing monitoring technologies.

In contemporary industrial settings, technological processes are pivotal for enhancing efficiency, reliability, and safety. These processes govern a multitude of operations, ranging from manufacturing to energy management, and their optimization is indispensable in today's fast-paced environment. For instance, the deployment of Smart Electric Meters (SEMs) has significantly transformed energy consumption monitoring, allowing for real-time data collection and analysis. This advancement not only facilitates efficient energy use but also plays a vital role in anomaly detection, which is crucial for identifying technical faults and preventing energy misuse (Kulkarni K, 2024) . Additionally, the complexity of time series data in various sectors, including manufacturing and healthcare, necessitates sophisticated detection systems to monitor and evaluate performance effectively. As such, understanding and improving these technological processes is essential for mitigating risks and enhancing operational integrity in diverse applications (Schmidl S et al., 2022) .

The increasing complexity and volume of data generated in technological processes necessitate the implementation of intelligent monitoring systems for effective anomaly detection. As industries embrace the Internet of Things (IoT),

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vast amounts of data are collected from machinery, presenting both opportunities and challenges in identifying irregularities. Traditional manual monitoring is inadequate due to the sheer scale of data, which often masks crucial failure signals. Instead, machine learning algorithms can automate the anomaly detection process, improving response times and reducing downtime. Studies indicate that the existing approaches mainly focus on cybersecurity, neglecting the unique challenges faced in industrial settings, particularly in incorporating machine learning within IoT ecosystems (Chevtchenko et al., 2023) . Furthermore, comprehensive evaluations of various anomaly detection algorithms reveal the need for tailored solutions that consider different data characteristics and operational contexts, emphasizing the importance of intelligent monitoring systems in this evolving landscape (Schmidl S et al., 2022) .

II. Fundamentals of Intelligent Monitoring Systems

The fundamentals of intelligent monitoring systems lie in their ability to leverage advanced data analytics and machine learning to enhance operational efficiency and reliability in various sectors. As illustrated in recent developments, technologies such as Smart Electric Meters (SEMs) play a crucial role in this landscape by providing real-time data collection that is essential for effective anomaly detection. The integration of anomaly detection systems not only helps identify technical faults and electricity misuse but also streamlines energy management processes, ultimately promoting sustainability within the energy sector (Kulkarni K, 2024) . Furthermore, the complex nature of time series data necessitates the application of specialized algorithms to accurately detect anomalies, which can signal critical issues ranging from manufacturing defects to healthcare concerns. A systematic evaluation of these algorithms reveals a diverse array of techniques, each with distinct strengths and weaknesses, underscoring the importance of selecting the appropriate method for specific monitoring tasks (Schmidl S et al., 2022) .

The architecture of intelligent monitoring systems is fundamentally comprised of several key components that work in concert to facilitate the detection of anomalous states in technological processes. At its core, these systems incorporate data acquisition units that continuously gather information from various sensors embedded within the operational environment. This data is subsequently pre-processed to eliminate noise and normalize the inputs, preparing it for analysis. Central to the architecture is an anomaly detection module, which employs sophisticated algorithms, such as those discussed in (Schmidl S et al., 2022) . These algorithms are critical in identifying deviations from expected patterns, detecting critical issues in real-time. Another vital aspect is the integration

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of hybrid observers, as described in (balluchi et al., 2017) , which enhance the systems capability to discern subtle anomalies resulting from intelligent attacks. Collectively, these components ensure a robust monitoring framework that significantly improves operational reliability.

1-Jadval

Component	Description
Data Collection Modules	Modules responsible for gathering data from various sources
Data Processing Units	Units that analyze and process collected data
User Interface	Interface through which users can view and interact with the system
Alerting Systems	Systems that notify users of anomalies or important events

Components of Intelligent Monitoring Systems Architecture

In the realm of technological processes, the role of sensors and data acquisition cannot be overstated, as they form the backbone of effective monitoring systems. By collecting real-time data, sensors enable the continuous observation of operational parameters, which is essential for identifying anomalies promptly. The integration of advanced analytics with sensor data allows for the development of sophisticated anomaly detection methods that can distinguish between normal variations and potential faults. For instance, the implementation of Smart Electric Meters (SEMs) significantly enhances energy management by offering precise monitoring capabilities, crucial for recognizing issues such as technical faults and energy misuse (Kulkarni K, 2024) . Furthermore, innovative approaches, such as conflict-driven anomaly detection, leverage both discrete and continuous observations to identify hidden anomalies caused by sophisticated intelligent attacks, ensuring a more secure monitoring environment (balluchi et al., 2017) . Thus, the synergy between sensors and data acquisition technologies is vital for maintaining efficient and reliable technological processes.

III. Techniques for Detecting Anomalous States

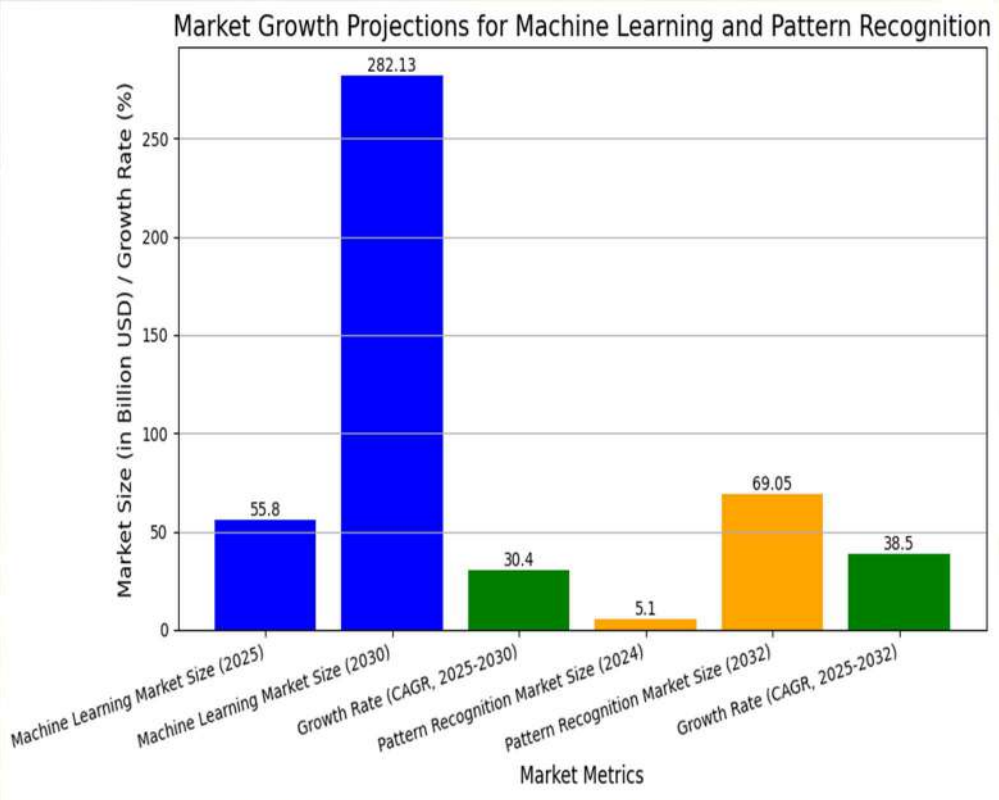
In the pursuit of effectively detecting anomalous states within technological processes, a diverse array of techniques has emerged, reflecting the complexity and varied nature of the data involved. One significant approach focuses on time series analysis, where specialized algorithms are employed to identify patterns that deviate from the norm, as highlighted by the comprehensive evaluation of 71 anomaly detection algorithms across 976 datasets (Schmidl S et al., 2022) . These algorithms are designed to handle large datasets that typically exhibit intricate

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behaviors, making the selection of the most suitable technique a challenging task. Additionally, conflict-driven anomaly detection has gained attention for its ability to address sophisticated threats, particularly those that may evade standard detection methods; this technique utilizes a combination of discrete and continuous state observers to pinpoint anomalies effectively (balluchi et al., 2017) . Such varied methodologies underscore the importance of adopting a multifaceted strategy in intelligent monitoring systems.

The application of machine learning algorithms in pattern recognition considerably enhances the efficacy of intelligent monitoring systems for detecting anomalous states in technological processes. Traditional methods often rely on supervised learning techniques that necessitate extensive labeled datasets, which can be time-consuming and impractical in dynamic industrial environments. In contrast, unsupervised machine learning offers a promising alternative by identifying patterns and anomalies without prior labels, thus streamlining data processing capabilities. For instance, the use of composite autoencoder models has shown significant potential in recognizing unusual behaviors within industrial control systems (ICSs) by analyzing time-sensitive and value-related data characteristics. Such innovations not only increase system reliability but also optimize operational efficiency, establishing a robust foundation for safe and sustainable operations in critical sectors like manufacturing and energy. Overall, the integration of advanced machine learning techniques in pattern recognition is vital for evolving effective monitoring solutions in contemporary technological processes (Choi W-H et al., 2024) (Choi W-H et al., 2024) .

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The chart illustrates the projected market sizes and growth rates for machine learning and pattern recognition from 2025 to 2032. The machine learning market is anticipated to grow significantly from $55.80 billion in 2025 to $282.13 billion by 2030, reflecting a compound annual growth rate (CAGR) of 30.4%. In comparison, the pattern recognition market is expected to increase from $5.10 billion in 2024 to $69.05 billion by 2032, with a higher CAGR of 38.5%. This indicates a growing adoption of advanced technologies in these fields.

In the context of intelligent monitoring systems, statistical methods play a vital role in real-time data analysis, especially for detecting anomalous states in technological processes. By employing advanced algorithms, such as those designed for anomaly detection, these systems can efficiently analyze vast quantities of streaming data generated in industrial environments. For instance, the development of algorithms that utilize machine learning and stream processing techniques can effectively identify deviations from established norms, thus facilitating proactive maintenance and operational efficiency (Sen RK, 2023) . Furthermore, a comprehensive evaluation of various anomaly detection algorithms on extensive time series datasets reveals distinct strengths and weaknesses, guiding practitioners in selecting the most appropriate methods for their specific applications (Schmidl S et al., 2022) . Together, these approaches enhance the reliability and responsiveness of monitoring systems, ensuring the integrity of technological processes.

IV. APPLICATIONS AND CASE STUDIES

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The application of intelligent monitoring systems for detecting anomalous states in technological processes is increasingly evident in various case studies, particularly within the realm of industrial environments. For instance, the integration of digital twins (DT) and autonomic computing (AC) principles in monitoring frameworks enhances the reliability of cyber-physical systems, as illustrated by a conceptual architecture that effectively identifies and responds to deviations in system behavior. This architecture facilitates the monitoring, analysis, and execution of reconfiguration strategies based on detected anomalies, ensuring operational integrity within complex systems, such as the European Railway Traffic Management System (Benedictis AD et al., 2023) . Additionally, research employing a hybrid observer for anomaly detection showcases the capability to identify sophisticated intelligent attacks that traditional methods might miss. By defining conflict types and establishing conditions for guaranteed anomaly detection, this approach emphasizes the critical need for adaptive monitoring systems in maintaining safe and efficient operations in technologically driven processes (balluchi et al., 2017) .

The implementation of intelligent monitoring systems in manufacturing and industrial automation plays a critical role in enhancing operational efficiency and ensuring system reliability. As manufacturing systems evolve into more intricate architectures, they become increasingly susceptible to faults and anomalies, which can significantly disrupt productivity and safety. Addressing these challenges requires robust fault detection mechanisms that can operate in real-time to identify issues as they arise. Research indicates that integrating advanced technologies—such as sensors and IoT devices—enables manufacturers to generate vast amounts of data, which can be leveraged for anomaly detection (Samadder M et al., 2023) . Moreover, the development of a conceptual model for intelligent fault diagnosis and self-healing strategies paves the way for more resilient smart manufacturing systems (Aldrini J et al., 2023) . Thus, the transition towards intelligent monitoring not only optimizes production processes but also fosters a proactive approach toward maintenance and operational integrity.

In the realm of intelligent monitoring systems, the deployment of anomaly detection mechanisms presents both significant benefits and notable challenges in real-world scenarios. These systems enhance operational efficiency by identifying deviations from expected behaviors in technological processes, thereby facilitating timely interventions to mitigate potential failures. For instance, a hybrid observer method illustrates the efficacy of conflict-driven anomaly detection, particularly in complex environments such as railway systems, where anomalies may arise from intelligent attacks that evade traditional detection methods (balluchi et al., 2017) .

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Conversely, the integration of heterogeneous components within networks can lead to increased risks of misbehavior and interaction anomalies, challenging the systems reliability and robustness (Benedictis AD et al., 2023) . Furthermore, the complexity of operational settings necessitates sophisticated architectures that can adaptively monitor and respond to anomalies, emphasizing the need for continuous improvement in detection methodologies. Thus, while intelligent monitoring systems promise substantial enhancements in safety and efficiency, they also highlight the critical need for intricate designs that address potential vulnerabilities.

2-Jadval

Benefit	Challenge
Real-time data analysis	Security concerns
Improved efficiency and productivity	Integration complexity
Predictive maintenance	High implementation costs
Enhanced decision-making	Data privacy issues

Benefits and Challenges of Intelligent Monitoring Systems

V. Conclusion

In conclusion, the advancement of intelligent monitoring systems for detecting anomalous states in technological processes is both a necessity and a challenge in todays data-driven environment. Given the complexity and size of time series datasets inherent in various applications, selecting the appropriate anomaly detection technique remains a critical task for researchers and practitioners alike. The study of (Schmidl S et al., 2022) highlights the diverse range of algorithms available, underscoring the intricacies involved in comparing their effectiveness, efficiency, and robustness. Moreover, the conflict-driven approach presented in (balluchi et al., 2017) demonstrates how hybrid observers can enhance detection capabilities, particularly in the face of sophisticated intelligent attacks. Collectively, these insights not only illuminate the current landscape of anomaly detection but also pave the way for future innovations, laying a foundation for further exploration and application in industrial contexts.

The development of intelligent monitoring systems is pivotal for enhancing the reliability and efficacy of various technological processes. Such systems employ advanced data analytics and machine learning to identify and respond to anomalies effectively. For instance, the integration of Smart Electric Meters (SEMs) exemplifies this, as they facilitate real-time monitoring and anomaly detection in energy consumption patterns, addressing issues such as technical faults and misuse of electricity (Kulkarni K, 2024) . Additionally, the diversity of anomaly detection algorithms further enriches these monitoring frameworks. A

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comprehensive evaluation of 71 state-of-the-art algorithms highlights their effectiveness in managing time series data, crucial for various applications, from manufacturing to healthcare (Schmidl S et al., 2022) . Collectively, these insights underscore the transformative potential of intelligent monitoring systems in detecting anomalies and promoting operational efficiency.

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