Optimizing Industrial Automation with IOt-enabled MEMS Devices for Smart Sensing and Actuation

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Abstract: - The research aims to understand how sensors work and collect, process, and integrate data into IoT systems in various application areas. It has the purpose of describing the performance of sensors and communication methods, as well as possible options for integrating with the IoT, providing recommendations to achieve better system efficiency and dependability. By conducting broad-based simulations and analysis of monitored parameters, the research demonstrates the dynamic nature of monitored parameters thus underlining the need for smart sensor selection and incorporation of sound data management strategies. Using diagrams helps in identifying signature patterns within the given data, trends, oddities, and even patterns. The work seeks to determine the factors that influence the choice of MEMS sensors, using weighted score analysis to provide a recommendation on selection criteria depending on the application of the sensors. Comparisons between communication protocols and choices of IoT connection also show that MQTT is a reliable and very low overhead protocol of communication while HTTP is faster and very compatible. IoT connectivity choices are mostly evaluated about their ability to fit various application environments. Finally, the paper also emphasizes the need for a sound approach to data management, and advanced analysis methods for obtaining valuable knowledge. In summary, this research enriches the understanding of IoT-streamed automated environments and provides implementation tips potentially useful in producing effective, resource-conservative, and human-centered IoT-enabled autopilot systems in diverse fields.

Key-Words: - Sensor Data Analysis, IoT-enabled Automation Systems, MEMS Sensor Selection, Communication Protocols, Data Management Techniques.

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1 Introduction

MEMS are becoming popular as miniaturizing tools for miniaturization due to their small size, low power consumption, and superlatively performance features. Out of so many fields and areas of usage of MEMS technology, MEMS-based robotic microgrippers have received a lot of interest and appreciation due to their ability to control the objects at the microscale level and to prove useful in material characterization. This paper gives an overview of contemporary MEMS-based actuation and sensing methodologies appropriate for microgrippers for the convenience of the reader. The survey encompasses an in-depth analysis of five primary types of actuators: Electro-thermal, electrostatic, shape memory alloy, piezoelectric, and electromagnetic actuators. Further, the existing approaches in sensing methodologies the capacitive, electrothermal, piezoresistive, and piezoelectric sensors are also presented. Consequently, the strengths, weaknesses, and uses of these techniques are well understood and a good insight into the ability of each technique is obtained. In addition, the paper explores potential breakthroughs of such electromechanically actuated MEMS microgrippers and related technologies to facilitate a further advancement of this field. This paper aims at presenting a clear understanding of the current trends in MEMS-based actuation and sensing so as to offer a strong ground for practicing engineers as well as researchers in the field of microscale robotics and manipulation, [1].

The IoT is a shift in network connectivity, where streams of sensors, devices, and services efficiently cooperate in several processes. This system organization that allows for sharing of data over the internet has greatly impacted many applications by providing such things as; Lower costs, Improved capability, Resource availability, and Automation. Industry 4.0 which shows that it has been incorporated into industrial processes, heralds a new era of manufacturing efficiency. However, the concept of the IIoT is not without great obstacles specifically pertaining to the protection of big data sets. The leakage of this information within these datasets is highly problematic concerning the privacy and protection of ideas and secrets. To address these concerns, there is a necessity to organized efforts to detect and manage susceptibilities in IIoT applications. Therefore, this paper’s objective is to identify and discuss regular input-output (I/O) design patterns that are characteristic of IIoT applications. In an attempt to do so, it wishes to delineate these patterns to successfully build abstract models that explicate data flow semantics involved in IIoT operations to improve security. In particular, it addresses communication protocols and aspects of I/O design patterns in edge devices that interface to ICS for process control and monitoring. This study, it carries the intention of offering insights into protecting the quality and privacy of the IIoT data, thus contributing towards the achievement of Industry 4.0 goals, [2].

Micro Electro Mechanical Systems (MEMS) have become very important technology that support the IoT, given it'sability to develop small, cheap, and high-performing sensors and actuators. This chapter digs deep into the impact that MEMS technology has provided on the development of the IoT. Although human sensory solutions are fairly effective within certain niches, they succumb to the flexibility and accuracy of MEMS sensors. MEMS sensors outperform human skills enabling simultaneous sensing of small levels of various parameters, for example, olfactory signals unnoticeable to human senses. Chapter 2 gives an overview of widely used MEMS fabrication processes that explain crucial micromachining methods used in MEMS manufacturing. From versatility, economic potential, and inclusiveness of possible applications, MEMS becomes a technology backbone for future IoT systems. By so doing, the chapter builds on this discourse and demonstrates the significance of MEMS in improving sensing systems while integrating IoT solutions into various fields, [3].

The Internet of Things (IoT) defines a connection of objects and/or users via the Internet. For the improvement and optimization of the IoT possibilities, the incorporation of the MEMS concept has become an ideal solution. MEMS technology allows for the creation of devices that have ultra-low power consumption while giving accurate results in a user-friendly way. The purpose of this paper is to identify multiple possibilities for MEMS in radically transforming classical IoT devices. More precisely, it ventures into critical areas including energy conversion, efficient sensor operation, fault detection, intelligent communication interfaces, and MEMS switching systems. Due to more focus on small environmental management of energy, IoT devices are developed to utilize natural power resources like hydropower, light power, wind power, thermal power, and solar power. MEMS sensors are the primary component in these applications, which is responsible for the performance and which delivers competent outcomes. By unfolding this analysis, the paper aims at explaining how and in which way MEMS technology can revolutionize the IoT systems and improve their efficiency and stability across all domains and industries possible, [4].

Over the past decades, the MEMs industry experienced an increase in demand for improvements in economically miniaturized sensors and components integrated with manufacturing technologies. Interestingly, it is the sensors' duty to identify different physical cues and then encode the information into either analog or digital formats. These variations can be used to check and monitor device variables since they act as signs. MEMS technology has quickly become an extremely practical approach to miniaturized sensors because of its small size, low power consumption, high performance, and compatibility with the use of batch fabrication techniques. This paper seeks to discuss the most current research trends in standard actuation and sensing mechanisms for MEMS based devices which are expected to transform many product segments in the modern world. In addition to details of actuation and sensing mechanisms, this article demonstrates important applications of MEMS technology to fill those interdisciplinary knowledge gaps. By understanding these mechanisms it is possible to select and design other new and more complex applications that use MEMS based devices to further open up the opportunities for future development in this area, [5].

The development of surgical and therapeutic tools has attracted progression from stiff serial manipulators to flexible or continuum robots that can only maneuver in certain parts of the human body. The need for increased procedural downsizing is a primary reason behind these flexible devices designed to open up new regions in the anatomy and provide access to new MIS solutions. For such systems, there are advanced solutions to perform navigation and control, yet existing production methodologies have restricted millimeter-scale development for these versatile end-effectors. Complex manufacturing techniques are indeed necessary to provide the next generation of highly efficient end effectors for surgical robots. This work eradicates this difficulty by proposing a new layered 2D production strategy derived from the manufacture of printed circuit boards. This approach enables one to build fully functional 3D mechanisms solely through the act of folding 2D layers of versatile materials that might act as structures, flexible circuits, adhesive substrates, or even electronic conductors. In this method, choices of materials used during the layer by layer build-up also enable direct incorporation of actuators, sensors, and electronics into the design for movement and articulation functions. To demonstrate the technology's usefulness, it fabricates three modular robotic components at the millimeter scale: devices such as sensors, mechanics, and actuators, of the building. Altogether these modules may be incorporated into transendoscopic systems enabling two-handed manipulation and resection, cutting, and should help to address the issues of challenging MIS operations made by endoscopy, and other flexible approaches. This study provides the foundation for new mechanism, sensor, and actuation technologies that can be implemented as a coherent system utilizing revolutionary layer-by-layer manufacturing strategies at the millimeter scale, [6].

This paper also presents a detailed analysis of the current applications of MEMS in robotics and industries besides examining the principles behind MEMS. MEMS technology has been employed in their use as actuators or sensors in many uses, including in ordinary consumer products, in automated production lines, and in industries. The application of novel polymers and composites like silicon along with innovations in the micromanufacturing techniques like micro-machining and micro-assembly has led to significant improvement in the utilization as well as effectiveness of MEMS application. Indeed, MEMS devices have demonstrated progressive improvements in miniaturization, resilience, modularity, personalization, and power conservation. This article provides an example of various applications in robotics and industries in terms of devices and technologies where silicon is most important in sensing applications. Additionally, trends and expectations for further development of MEMS applications are investigated, which will help to predict the future development of this rapidly emerging field. The reason for undertaking such a detailed discussion is to gain some valuable information on today's state of MEMS technology and how it will impact robotics and industrial system fields along with a glimpse into the potential of advanced evolution in the future, [7].

MEMS technology has come a long way in the last three decades showing a revolution in sensor and actuator demonstrations. Originally, the abbreviation MEMS referred only to electromechanical sensors or actuators made of semiconductors, although this idea was mainly associated with the United States. On the other hand, this technology was referred to as Microsystem Technology in Europe and as micro-mechatronics in Japan. Currently, MEMS includes devices, sensors, and actuators ranging in size from 0.1 to 1000 micrometers in terms of size, without reference to their material base: silicon, glass, or metal. This chapter presents the historical background of MEMS, the development timeline of MEMS, and the global naming convention of MEMS. It also ventures into future trends currently affecting the MEMS industry. In addition, it provides an overview of the materials used in MEMS sensor and actuator manufacturing to describe the strengths and limitations of each material. Last but not least, it examines the different types of MEMS sensors and actuators, their uses, and the latest technology developments for MEMS sensors and actuators, which are assumed to be the point of focus study for this all-encompassing study. In this respect, the discussed chapter provides an understanding of the evolution of MEMS technology as well as its current state and future trends and makes use of it as a foundation in the development of sensors and actuators, [8].

Continuous escalation of demand for WSN has forced the discrete use of expensive accelerometer components, prompting the search for their better substitutes in the form of MEMS-based sensing elements in static, as well as dynamic, modes of implementation. Due to its small dimensions and reasonable price, MEMS accelerometers have been used as a viable solution for multi-tasking and monitoring applications. This chapter provides extensive information on the basic architecture, working principles, and real-world application of MEMS accelerometers. It offers valuable recommendations on the choice of experimental configurations, signals conditioning, and data analysis procedures which are crucial in developing comprehensive performance evaluation systems. Performance evaluations are made with several excitations such as sinusoidal, impulse (hammer test), and random excitations. The subsequent analysis includes performance evaluations quantified by calculations and discussions on frequency response functions, signal-to-noise ratios, and phase distortions of the system. Further, recommendations for the implementation of MEMS accelerometers are provided in relation to packaging, the formation of intelligent vibration monitoring nodes, and the determination of condition-associated data. From this analysis, this chapter intends to provide useful information and recommendations to the researchers and practitioners for various monitoring and control applications using MEMS accelerometers for the effective implementation and application of MEMS accelerometers in everyday applications, [9].

The field of industrial electronics has therefore experienced important changes in the last little over two decades due to the introduction of smart systems that have brought about the aspect of functionality. Robots can perform some of the once manually intensive operations, sometimes in conjunction with the human operator, today. This change has been driven by the incorporation of micro-sized sensors that capture process data required for industrial applications accurately and consistently improve system performance. This direction has been complemented by the development of motion control systems, which allow adapting the equipment for use in aggressive industrial environments and maintaining its performance at a high level. Furthermore, the dependence on data concerning operation and control of the sensing data, through communication networks has enabled real-time processing and decision-making on the industrial processes. These elements include fault diagnosis strategies that automatically help to identify abnormalities and prevent the breakdown in the system. These developments further support a revolution in industrial processes that enable smarter systems in utility enhancement and optimization. This work aims to investigate the processes that have enabled the incorporation of these capabilities into the industrial domain, as well as look at the future prospects for further development. Hence, the nature of the discussion in this article is to share some lessons from the journey taken and, therefore, give an idea of what more could be expected from smart systems in industrial electronics, a field that is on a continuous course of transformation, [10].

The emergence of the IoT opened a new generation of pervasive computing by delivering Internet access to applications across the globe. In 5G related IoT applications, high-speed transport of data while keeping information up for collection and analysis links together billions of things. However, the centralized designs proposed in related works have problems such as access control methods, latency in data access, and protocol dependence, which may not be able to meet the needs of future applications. These designs are very susceptible to single points of failure and consequently entail high computational overhead. To address these constraints, there is a need for better decentralized access control to construe the D2D communications In IoT enabled industrial automation sectors. With everyone depending on centralized solutions, security, and privacy come out as key factors. In response, this paper performs a comprehensive analysis of state-of-art proposals that leverage 5G IoT as the base for blockchain-based industrial automation in a broad spectrum of applications: Smart Cities, Smart Homes, Healthcare 4.0, Smart Agriculture, Autonomous Vehicles, and Supply Chain Management. From prior thinking, it also becomes evident that blockchain is the technology of choice that has the potential to revolutionize today's and future industrial uses by providing the means for defined granular decentralized access control. Blockchain enables quick tracking of the transactions and the database records to ensure that there is conformity and anonymity as mentioned in the aforementioned industrial areas. The article also discusses remaining issues and opportunities regarding 5G IoT to support blockchain-based industrial automation. Last but not least, a comparative analysis of current ideas is presented together with the usage of several indices, enabling end users to make appropriate choices in favor of some of those plans. This research aims to bring knowledge in the application of blockchain technology within the industrial automation revolution, alongside the issues and opportunities faced in the field, [11].

2 Research Methodology

The evaluation of the environmental parameter through a multilevel IoT architecture. Specifically designed for the Hyderabad region, the system should help to assess changes in the environmental parameters efficiently. Protocols of the II tier architecture of the system include a number of different sensors that are grouped into five sensor nodes and can be switched on by either using the switches in the gateway or via a webpage interface. There are several sensors within the described system, these sensors gather information which is next sent to a slave controller known as a PIC. After this, the slave controller sends the extracted data to a master controller (Raspberry Pi) that acts as a gateway between the sensor nodes and the cloud. The data is then loaded on the cloud by the master controller and written to a webpage via HTTP. Also, the data is sent through GSM in the form of SMS messages. The practical reality of the system was accomplished when tests were performed under different environmental contexts and heights. Using Standard Meteorological data, retrieved from the internet, it was concluded that the data collected was accurate indicating that the system was very effective. For a 15-day period in June 2018, the system tracked alterations in the climatic conditions of the Hyderabad region. The information thus collected was in turn provided to local farmers to enable them to make choices on what crop to grow and how to cultivate them, especially cotton, jowar, and red gram crops. In this way, the paper is designed to make a constructive input into the collection and analysis of environmental data and help with decision-making in the agriculture of the area, [12].

Environmental pollution as an issue that complicates public health and safety; thus, precisely identifying pollution levels by spatiotemporal resolution within the microenvironment is essential. Miniature environmental sensing devices have continued to be developed successively and microelectronics and communication technologies, therefore giving rise to wearable devices, particularly for environmental monitoring. These wearable devices provide the added advantage of obtaining detailed geo-tagged information in high resolution, which will enable better analysis of the relationship between the physical, social, and built environment and human health and activity. This paper aims to present a synthesis of current findings and advancements in the field of wearable environmental monitoring systems or WEMS for IoT. The paper provides specific accounts of current WEMS development and classifies them according to whether they use COTS sensors or their own developed sensors. Secondly, there is the categorization of WEMS based on wearability, and lastly, there is a single summarised outline of the key characteristics of commercially available wearable environmental monitoring devices. Furthermore, it highlights the major concerns and possible problems regarding WEMS before proposing directions for future research. This review paper categorizes existing studies and technologies, establishes an integration of state-of-art research areas, and provides outlooks and suggestions to assist the researchers and developers in future refinements of wearable environmental monitoring technology, [13].

The proliferation of ideas on the Internet of Things or IoT that L initiated, controlling the electronics through the network has become a mainstay of society. This control is facilitated by the assessment of values of factors that provide essential information on the performance of these devices. At the same time, the collected data is relayed from the monitoring device and saved on the cloud for use by numerous apps and support processes. This monitoring includes environmental observation that can be carried out through the help of sensors such as humidity, and temperature. Raw data that has been collected may be put to use to activate processes like the extrinsic control of cooling and heating equipment or initiating detailed long-run statistical control. In this context, a system is developed through Arduino UNO combined with raspberry pi, HTU 211D sensor device, and ESP8266 Wi-Fi module. This setup presents experimental results for real-time temperature monitoring, humidity, and soil moisture content. Temperature and Humidity measurement is achieved by the HTU 211D sensor and this part is being implemented using Raspberry Pi. Further, temperature sensors are placed around to display information stored in different gadgets/devices. Through the ESP8266 Wi-Fi module, data recorded is easily stored and transmitted to the cloud storage facilities. By this overlapping structure, the MEMS system provides an all-in-one solution for environmental parameter tracking and decision support in numerous processes, [14].

The advancement of versatile sensors for measuring various parameters of the surrounding atmosphere, humidity, temperature, and flow rate is highly essential in application areas for IoT, healthcare, and interfaces. Here in this work, a new type of single-layered sensor device is developed which can sense the humidity, temperature, and flow of the air. The sensor utilizes a microheater formed with bending Pt microlines, which performs dual roles, proper Joule heating for sensing humidity and airflow, and a stable temperature measurement using a thermistor. Consequently, the integration of the GO in the humidity sensor leads to the introduction of salient temperature dependent characteristics such as the ultrahigh sensitivity within a very short span of time and, a large sensitivity range at ambient temperature. Nonetheless, sensitivity reduces to temperature increases, to give more attention to temperature effects. The flow sensor has a direct proportionality between sensitivity and voltage; therefore, sensitivity variation is attainable through a change in the voltage supply to the microheater. More significantly, the three sensors work independently and produce different output signals, facilitative of multiparameter sensing to survey diverse human activities like respiration and contactless sensing feeling. This work presents a detailed development of an affordable, portable, and scalable multiparametric sensing device utilizing a microheater and expands on it into emerging markets such as IoT, healthcare, and technical human body control. The proposed approach is typical for original method improvements of studying the sensor technology for the application's demand shifts, [15].

Micro-Electromechanical Systems (MEMS) inertial sensors and the possible use of MEMS technology in navigation, for readers not very familiar with the topic. MEMS accelerometers, working rather the same as typical components from electromechanical systems, are, in fact, stepping forces through movement into electrical signals relating to acceleration. Likewise, MEMS gyroscopes are categorized according to the transduction mechanism they employ, and the pros and cons of each are briefly summarized here. To help the readers understand about the MEMS inertial sensors, this chapter reviews various types of gyroscopes familiar to most readers. Normally, the inertial measurement units in MEMS include three-axis accelerometers and three-axis gyroscopes that make it a useful navigation solution. It also goes further into specific factors associated with MEMS sensors choice and use, the position, orientation, and motion data essential for navigation. However, we find that MEMS sensors become a favorable solution for navigation engineers, especially in navigation conditions in which GNSS might not suffice. This paper aims to present the readers with the understanding of the advantages and possible domains of utilization of MEMS inertial sensors to foster the appropriate and judicious use of MEMS technology in navigation systems, [16].

The integration of various devices and systems, through the Internet has led to a new age of smart technologies where information sharing and system control are two-way. In the Internet of Things (IoT), a host of sensing devices when connected can improve their decision-making abilities. One significant innovation in this area is the miniaturization and manufacturing, using the principles of microengineering, of sensors regarded as being at the cutting edge of the electronics industry. Ranging in size from a few millimeters to nanometers, such Sensors are used in different fields of human endeavor in the social as well as in the economic world. Of all the industrial devices utilizing MEMS technology in IoT systems, there are the following: There are the following; soil moisture sensor, temperature sensor, gyroscope, accelerometer, biosensor, pressure sensor, magnetometer, optical actuator, and gas sensor, among others. Due to the small size and low power consumption of these miniaturized MEMS devices, it forms highly advantageous to the macro type. As a result, IoT systems widely use MEMS devices due to their low power consumption, small dimensions that do not take up much space, and the development of smart technologies, [17].

Robotic object handling, very often crosses paths with contact force regulation and approach motion configuration. These problems may be solved by the MEMS sensors themselves; at the same time, they suggest new opportunities. In this study, we assess the usefulness of touch, force, and pressure sensors that were developed based on MEMS technology as well as current MEMS barometric sensors. MEMS platforms for their part in a single use or in a system with additional sensors provide a lot of use in equipping robots to sense contact forces, slippage, and the distance of objects for easier handling. It provides a quick introduction to all the sensing modalities and mechanisms including capacitive, resistive, piezoresistive, and triboelectric in combination with flexible material technologies such as polymer processing and MEMS-integrated textiles for flexible and snake robots. Using MEMS sensors or micro electro-mechanical systems within robotic hands the various human finger things like grasping, hardness, and stiffness feelings can be simulated all without adding size or mass. Moreover, MEMS technology is a promising one for developing the new generation of microactuators and microsensors, and miniature thin motion systems (micro-robots), such as micro-robots for medical, security, safety, and environmental management applications, [18].

Also concluded that as the use of IoT devices has grown vastly, so has the interest in cloud solutions that can address such a scale. In this line of thinking, the advent of fog computing and the synergy between fog computing to cloud computing models have emerged as fundamental for providing a decentralization of the cloud and providing services closer to the end-users. This article performs a survey on the application layer communication protocols for IoT public interest communication and their VM structure and suitability for fog and cloud IoT systems. First, potential candidates for protocol implementation, including the request-reply and publish-subscribe protocols, are described. The paper then provides an analysis of several protocols, concerning their main characteristics, and bottlenecks that are associated with them, including latency, energy consumption, and network throughput. These gains are then used to sort the protocols within each of the segments to IoT, fog, and cloud, thus enabling further discussion on protocol choice, interface, and connected overall system. It is hoped that this study will be of great value to system architects and protocol designers who select communication protocols for an integrated IoT to fog to cloud systems architecture, [19].

The growth of IoT has created discourse on the suitable protocol stacks for future expansion. This paper presents a full characterization of the currently talked about protocol stacks with the overarching aim of establishing which solution aligns with prototypical IoT scenarios. More particularly, this research analyses NDN together with two current application protocols based on the IPv6, CoAP, and MQTT, in several scenarios running on a big-scale IoT testbed. These setups are for the single hop and the multi-hop, such that we have planned traffic and unplanned traffic in one setup to make the comparison of the different loads of traffic. The research findings highlight several key observations: First, it is resource-friendly when implemented on nodes; second, it is robust and resilient in multi-hop networks; third, the IP protocol is lighter and faster in single-hop networks. In particular, it was discovered that NDN-based protocols are significantly more efficient in maintaining flow balance as compared to UDP-based IP protocols when fewer correction procedures are needed. The rationale of this literature review is to provide important information on the comparative effectiveness and versatility of various protocol stacks for IoT applications for researchers and practitioners in the field to make informed choices, [20].

The IoT as a disruptive technology that will revolutionize human interactions and interactions between individuals, industries, and businesses by connecting them and fostering creativity like no other technology. When IoT technologies became widespread, a large number of network protocols technologies, and standards for applications and services appeared. Such are Narrowband IoT (NB-IoT), LTE-M, 5G, LoRaWAN, Message Queue Telemetry Transport (MQTT), Constrained Application Protocol (CoAP), and the Open Mobile Alliance (OMA) for Machine-to-machine (M2M) communications. IoT is rich in the following commercial prospects due to the continuously growing IoE with respective connected units that generate about five quadrillion bytes of data daily. Nonetheless, there is still a problem with security, and as IoT grows even more, it can become catastrophic due to the vulnerability of IoT ecosystems and generally unsound procedures to install secure software updates. To address this problem, this article presents three different models employing that employ the CoAP and MQTT application protocols for Over the Air (OTA) distribution of software updates and security fixes to IoT devices. To achieve this, the usefulness of different protocols in the proposed models and applications is evaluated with a view of providing guidance on the most effective method of keeping IoT installation secure and ready for use, [21].

Analyze what is known as the Internet of Things (IoT), namely the marriage of physical things ranging from sensors to human beings and actuators and computer hardware all connected to a worldwide network. In industrial settings, IoT devices are one of the key sources of data giving a broad perspective of productivity. Thus, despite the large volume and variety of such information and its real-time nature, there are serious difficulties with real-time data collection, analysis, and decision-making. In order to address these problems, this study develops a solution by proposing a conceptual design of an IoT-based Industrial Data Management System (IDMS) that can efficiently and conveniently handle large industrial datasets for online monitoring and to support smart manufacturing. The framework consists of five essential layers: hardware, connection, platform, storage, and software layers that complete a service-oriented architecture addressing consumer-oriented needs. The applicability of the proposed framework is illustrated through an example of a smart factory integrated with a set of edge computing nodes and controlling manufacturing equipment over distant industrial networks for collecting and processing both routine data and significant events. First and foremost, the data collected by the system employ the latest communication standards to transform the received data into such valuable information as to generate the precise estimate of the production line and avoid occasional slow downing of the work. This literature review sets the scope of the research by outlining the literature on the real value of IDMS in the industrial IoT context as well as the advantages of using such a framework for real-time manufacturing process enhancement, [22].

Both communication and processing features in order to proceed with smooth intercommunication with each other and also with Internet resources. This connectivity also enables the delivery of various tasks as well as life easier for the user hence enhancing their quality lives. Similarly, the advancement of IoT within the automotive industry has created innovative connected vehicles with Internet of Things technology giving rise to the Industrial Internet of Things (IIoT) for progressing the Cyber-Physical Systems for communication between man and machine. However, the elements of this network are diverse, and heterogeneous and produce a huge amount of data, which creates problems for conventional database management systems. Therefore, IoT data management systems require some unique principles to be incorporated when addressing this data excess. To address these issues, different solutions have been proposed: middleware solutions for overcoming data integration issues, and architectures for storage and indexing of both structured and unstructured data often utilizing NoSQL databases. This paper seeks further to outline and elaborate basic concepts in managing IoT data, review existing strategies, and discuss promising techniques in the field at the same time as it will indicate crucial research challenges and further openings in the field. In this literature survey, the authors attempted to offer elaborate information and suggestions to promote and advance the study and progress of IoT data management, [23].

Robotics that has prompted the development of a new rut that is referred to as the Internet of Robotics (IoR), this is a revolution in almost all aspects of life. Today, IoR is still considered to be in the process of its development and it will be able to invade almost every other sector and market. Nevertheless, IoT integration in Robotics brings some issues that need to be solved to allow a large-scale application of integrated systems. These difficulties involve design aspects, security questions, sensor solutions, and extended-range communication. To address these challenges, this paper presents an InterBot 1.0 solution, an Internet-of-Things-based Internet of Robot system. InterBot 1.0 will allow the user to control this process in real time, with particular emphasis on temperature, humidity, and gas detection. The system also possesses well-developed communication interfacing features such as a 2.4GHz 6-channel remote and short-range communication by HC-05 Bluetooth. InterBot 1.0 uses IoT chiefly via ESP8266, thus facilitating smart connection and data transfer among the various modules. Additionally, collected data can be remotely visualized using live graphs on the ThingSpeak.com platform that may help users understand current environmental conditions. The outcome of the study on InterBot 1.0 is used to highlight the effectiveness of the given framework in observing RT environments, indicating the possibilities to mitigate the difficulties of IoT-based robotics systems, [24], [25].

The characteristics and future expansion of complex programs that would be useful in handling and processing big data provided by assorted sensors. They are essential in supporting decision-making that would allow systems to optimize their operation as a response to changes in the environment's circumstances. In the recent past, the number of IoT-based reasoning systems developed has steadily increased, however, a full-scale evaluation of these systems especially when implemented in complex scenarios has not been done enough. In response to this challenge, developers have been forced to design architectures using experiences obtained from past projects and this has made a big influence to the performance and scalabilities of the systems. To this end, this paper aims to fill the gap by providing the findings of a performance analysis of numerous implementations of context-aware management architectures for IoT-based smart cities. The study assesses the social and technical feasibility of various choices of architecture as well as gauges their utility in supporting 'real-time' automatic decision-making activities based on emerging information. The experimental results show the great effect of architectural decisions on the scalability issue as well as prove that employing the information transmission from tens of thousands of sensors possesses the possibility to apply automatic decision-making in the corresponding environment. Thus, with the findings on the performance impact of varying architectural designs for IoT-based smart cities, this research enhances the body of knowledge in the development of smart IoT-based city solutions, [26].

The context of Industry 4.0, describe the contemporary manufacturing environment that changes the basic nature of human-to-technology relations. At the core of this transition is the IoT and CPS technologies connecting and interacting with people and devices. In this paper, the author seeks to analyze the nature of this interaction with a special focus on its importance seen within the context of the Deming standard cycle. Consequently, the paper's objective is to position human-machine interaction at the center of operational improvement and learning through the application of the Deming cycle on the seven major technologies comprising Industry 4.0. The Fourth Industrial Revolution is defined by the profound changes in the labor market, which must make traditional approaches reviewed. Under this account, the paper calls for a new form of understanding Industry 4.0 from a human-centered perspective. In this paper, to elaborate on the role of the human factor, the 'Sand Cone Model' is discussed to provide a framework for understanding the mobility and changes in the workforce and the effects on industrial processes. Presenting a concept of a new theoretical approach, the paper aims to further the understanding of the relationship between workforce quality skills and every quality indicator achieved in industrial processes. Since the proposed framework discusses how the competencies of the workforce affect efficiency and effectiveness, the intention is to shed light on the human-automation interface from the Industry 4.0 perspective with the view of improving productivity and performance, [27].

Smart focused on Smart cities, which outlines its approach to the development of cities by incorporating innovative technologies to improve services delivered to citizens. As a result of optimizing real-time control of physical infrastructures and offering enriched relevant information in diverse domains including transportation, health, security, and farming, smart cities have become critical in meeting new demands of cities. However, given the fact that numerous applications within the smart city concept involve the collection and processing of large volumes of sensitive information, questions related to security and privacy remain acute. This paper presents an outline of the breadth of the primary uses of smart cities and highlights the urgent need to tackle concerns over security and privacy in smart city systems' architecture. When smart city systems incorporate large data from a wide range of stakeholders, they open themselves to numerous threats of insecurity and privacy inversion in layers of the structure. Therefore, it is necessary that all stakeholders in smart cities, including those who design and deploy the applications, study and address these problems. Besides describing the key security and privacy concerns associated with smart city architectures, this paper also explores current protection solutions in the context of protecting critical information. Therefore, through a discussion of current approaches and methods to the security and privacy of smart city applications which heavily rely on information and communications technology applications, the paper aims to identify lessons learned and developments within the discipline. In addition, this paper points out the following directions for future research and development: Further research should be devoted to reducing the limitations of the performance and to enhancing the security and privacy protection for smart city infrastructures.

Based on the flowchart in Figure 1, the presented framework outlines a process of synthesizing a complex system for developing an intricate research program that can increase the effectiveness of sensor-based systems. Starting with sensors and metering data acquisition, the use of two primary data transfer protocols: MQTT and HTTP is used to capture multiple streams of data. Next comes the sensor analysis whereby activities like the selection of the sensors and comparison of the sensors again with set criteria like the sensitivity, response time power consumption, robustness, and reliability of the sensors. At the same time, analyzing the available connectors, Wi-Fi, Bluetooth, and LoRaWAN, to determine the best one for implementation is provided. The flexibility of collecting data using the sensors and also analyzing the data real time contributes to the development of accurate perceptions and control being a result of an added feature to enable the plotting of historical data together with the real-time data. In addition, energy efficiency simulation allows for determining the system's response to the potential change in operating conditions, which forms a critical consideration in system design and improvement. Moreover, the program is also human-oriented, which includes training, system acceptability analysis, and HMI optimization to improve the effectiveness of the system. Altogether, this comprehensive approach leads to highly valuable research work designed for the enhancement of capabilities and the usage of the sensor-based systems which evidences the interdisciplinarity of the undertaken research as well as its relevance to and potential benefits for multiple stakeholders.

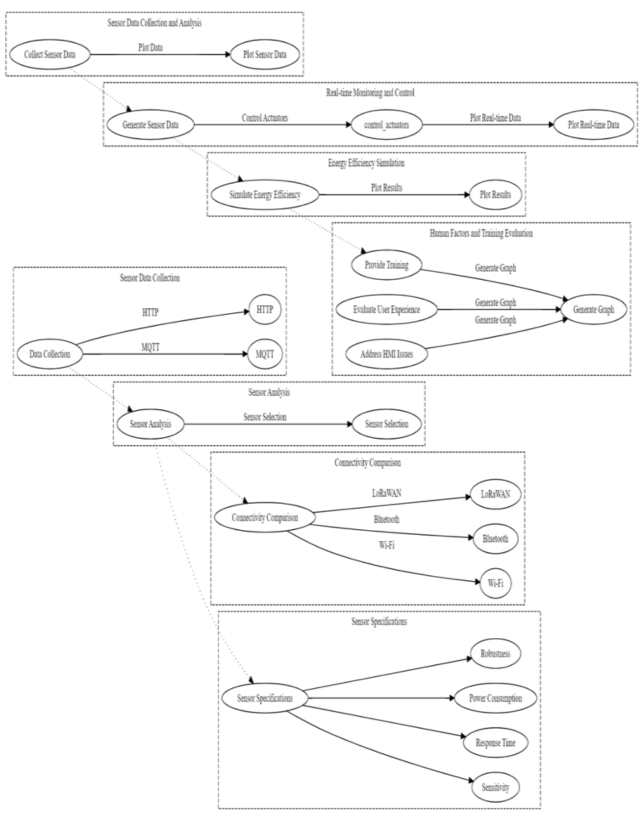

Fig. 1: Flow chart of Research work

3 Research Gap

The literature review offers a diverse setting of research events revealing different types of scenarios of sensor-based systems ranging from environmental monitoring, wearable devices, IoT, and further development of sensor technology among others. However, looking at this plethora of literature, several gaps appear which should be addressed further. Firstly, a large number of current papers has been dedicated to exploring the environmental parameter monitoring and IoT application in certain fields, however, there are not enough overall research programs addressing the sensor data gathering, analysis, connectivity, real-time, energy efficiency, and human factors assessment in one context. This broad area of research suggests that future investigations in sensors need to incorporate cross-disciplinary investigations that address various aspects of sensor-based systems so that the differences in relevant approaches can be explained and a more complete picture of the possibilities and challenges in building such systems provided. Secondly, there are disparities that center on speed, accuracy, range, precision, repeatability, stability and reliability, compatibility of the sensors with other subsystems or components, integration and connection possibilities of the identified sensor technologies, and their power consumption. Therefore, in the field of wearable technology and multiparameter sensors new research on improving the efficacy, dependability, and compatibility of the sensors used across different applications is still considered relevant. Moreover, the imperatives of implementing sensors in the IoT structures result in a set of concerns regarding data transfer, computation, and protection that need to be solved by emerging approaches. To overcome this gap, this research work focuses on the study of an overall framework for sensor-based systems that covers data acquisition, data analysis, connectivity comparison, monitoring, energy efficiency simulation, and human factors assessment. In turn, this work will not only help to overcome the aforementioned difficulties but also provide comprehensive approaches to realizing sensor-based systems for a wide range of applications. It is the goal of this research to extend the operationalization of sensors and streamline the IoT applications to better serve in decision-making and further develop the applicability of sensor-based systems across different fields.

4 The Objective of the Work

- ✓ To develop a robust framework for sensor-based systems, it aims to integrate data collection, analysis, connectivity comparison, and real-time monitoring, addressing the challenges associated with sensor technology integration and system optimization.
- ✓ To enhance decision-making processes by providing actionable insights derived from sensor data analysis, energy efficiency simulation, and human factors evaluation, thereby optimizing system performance and usability.
- ✓ To evaluate sensor technologies, this work seeks to assess the effectiveness of different sensors through rigorous evaluation against specified criteria such as sensitivity, response time, power consumption, and robustness.
- ✓ To explore connectivity options including Wi-Fi, Bluetooth, and LoRaWAN, to determine the most suitable option for different application scenarios, considering factors such as range, data rate, and power efficiency.
- ✓ To validate real-world applications across diverse domains such as environmental monitoring, industrial automation, and healthcare, assessing its effectiveness and applicability in practical scenarios.

5 Result and Discussion

5.1 Sensing Requirement

Temperature measurement is important in a number of applications including heat treatment and chemical reactions as well as HVAC applications. Temperature sensors are used for detecting the operating conditions; to prevent overheating and also to retain the quality of the product. There is always demand for pressure sensing for measuring fluid flow rates, and hydraulic and pneumatic systems. It is used for monitoring pressure within certain limits, for sensing and controlling leakage, and ensuring the safety of the equipment. Relative humidity levels control the quality of air and materials in industrial sectors such as manufacturing, warehousing, and cleanrooms. It is used in vapor control, to protect against rust, and in the preservation of products. Measuring the flow of fluids in the industrial system needs to be accomplished to maintain process control in chemical processing, water treatment, and the oil & gas industry. Flow sensors allow the measurement of flow rates, identification of possible leaks or blockages, a proper utilization of the resources. Level sensing is required for measuring levels of liquids, solids, or even granular materials in tanks, silos, and storage vessels. It assists in avoiding overfilling or draining as well as controlling stocks, and the safety of operations.

With reference to Figure 2(a) the presented program is used to mimic data capture from various sensors within a given time frame and builds a graphical view of the sensors over time. The plot shows five individual lines that show the data from sensors that measure temperature, pressure, humidity, flow rate, and level. Every line plotted on the figure refers to a certain sensor while the time span is lying along the x-axis and sensor readings along the y-axis. When looking at the graph, it is possible to see that there are oscillations in the values received from the sensors which means that the monitored environment is rather volatile. Details such as temperature, pressure, humidity, flow rate, and level fluctuate in time making the system more complicated. At the same time, the observed data actually does not show any direction for the trend and could be interpreted as stochastic, which means that the processes within the space are random or fluctuation-dominant. Nonetheless, cyclic shapes or 'peculiarities' can be distinguished at a finer level of analysis in any case. It is easy to examine trends within the sensor data through the use of the graph and can be used to analyze the system's behavior and performance. There could also be a near analysis of the alist which may involve the use of statistical analysis of the proposition or the use of machine learning algorithms to identify other patterns within additional data sets. In general, such kind of graphical representation gives a clear picture of the observed measures of a system under surveillance to the reader of the log file besides being very useful in the monitoring and analysis of the system.

The recorded sensor data demonstrates a spectrum of values, which reflects the changing conditions of the indexed space. Fluctuation of temperature is greatly observed based on the results where the minimum temperature recorded is 13.33°C and the maximum temperature recorded is 96.69°C. Pressure measurements are in the range of 16.11 kPa to 97.71 kPa which shows that the pressure of the system varies. Relative humidity values also range going as low as 16.01% showing variations in moisture content and high of up to 84.45 % . Flow rates vary widely from 5.94 L/min to 86.47 L/min due to alterations in fluid dynamics, or, the flow control mechanisms. Also, the obtained levels differ from 9.55 to 99.88, which indicates that the level measurements vary in the range of the monitored system of the liquid levels. The observed fluctuations of the sensor values indicate that the system behavior is very nontrivial and suggests the necessity of having multiple and detailed monitoring and control approaches. The diversity of acquired sensor data is particularly useful for understanding the behavior and performance of the given system and formulating corresponding intervention strategies. However, it also highlights the importance of the high reliability of average and dispersion calculations to find regularities and exceptions easily. Additional sophistication of the analysis to include the application of statistical analysis or machine learning can add enhanced insight into the performance of the systems so as to facilitate optimization, predictability, and control of risks. In summary, the recorded sensor signals offer an extensive ground for inspecting the complexity of the observed system and create the basis for future exploration and innovation in related fields.

As indicated in Figure 2(b), ubiquitous vibration is crucial for identifying machinery defects, mechanical looseness, and high degrees of wear in rotating equipment including motors, pumps, and turbines. Piezo vibration sensors, particularly, help in the prevention of failure that is time-consuming and decreases the durability of the equipment.

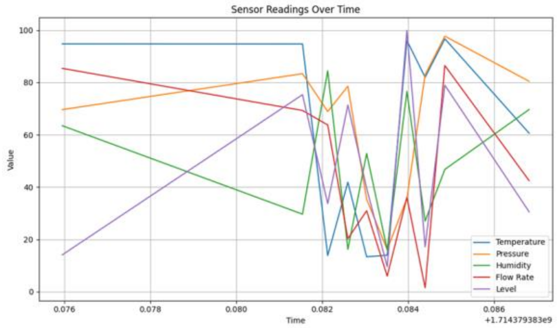

Fig. 2(a): Sensor Reading over time

P accreditation of acceleration is appropriate for measurement of movement, shocks, and vibration in industrial equipment and structures. Accelerometers are employed in condition monitoring systems, structural monitoring, and component identification solutions. There are several specific uses of these gas sensors; they are used in industries to measure the level of dangerous gases or Volatile Organic Compounds (VOCs). In their simplest form, gas monitoring serves as a measure of safety to the worker's safety and compliance with regulatory requirements while also providing an early indication of the possibility of hazardous circumstances within a given facility. They are applied to quantify the intensity of light indoors and outdo or outdoors and used to detect light intensity in the processes like photolithography. Light intensity sensing is applied to correct the problems dealing with optimum lighting, efficient energy usage, and steady output of products. Those who are responsible for the operation and control of electrical systems, equipment, as well as energy will greatly benefit from the monitoring of electrical parameters including voltage, current, and power consumption. Measurement transformers help to distribute the load, detect defects, and increase energy efficiency. From equation 1 where T is temperature, t is time, x is position in the room, and α diffusivity of the material of construction.

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \quad (1)$$

The recorded sensor data includes a range of values assessing the contending and variable state of a given environment. The vibration level which falls between 15.47 to 69.12 is the information about the degree of mechanical oscillation or disturbances in the system. Acceleration values range from 5.59 and 93.65 which indicates changes in the velocity of objects in the environment. Derived gas concentration values from 7.88 to 92.54 reflects the changes in the presence or concentration of gases that may point to poor air quality or unsafe environment. Light intensity values ranges between 13.81 to 97.04 as a result of variations in the surrounding light intensity which could affect the visibility or conditions of the environment. Electrical measurement values that fall in the range of 39.83 to 94.53 describe the electrical tendency of the system such as voltage, current, or impedance. The variability in the density of the sensors depicts the sample heterogeneity, this is the reason why information from as many sensors as possible should be gathered to grasp a variety of sides of system behavior. In this way, such as multifunctional sensor data can be useful to clarify changes in the physical, chemical, and environmental conditions inside the system. By doing so, the present results imply that decisions, predictive maintenance approaches, the entirety of the system, and overall safety can indeed be influenced significantly through proper interpretation and analysis of such data. Moreover, the high variability of sensor values only serves to emphasize the importance and potential of data pre-processing and knowledge extraction as well as anomalous event identification. Further, applying statistical forecasting, and machine learning techniques and solving them or anomaly techniques can help to see patterns, trends, and abnormalities for early intervention and optimization. In general, the recorded data of the sensors are valuable for controlling and handling the complexities of the investigated monitoring system, and provide base data for future studies and enhancements in related areas.

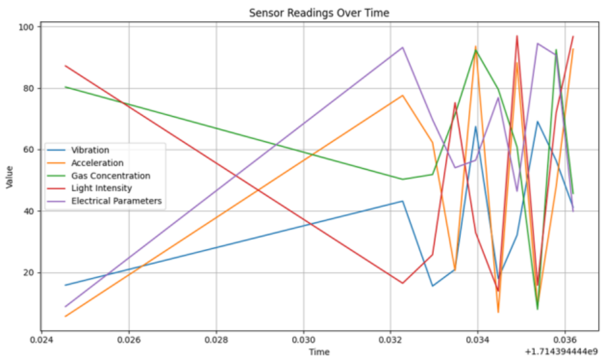

Fig. 2(b): Sensor Reading over time

5.2 MEMS Sensor Selection

Pressure gauge measures change in the pressure of gases or liquids. Temperature Sensor is an important application that measures the variance in temperature within the external environment. The accelerometer measures acceleration itself and as such can measure movement, vibration, and tilt. A gyroscope refers to the measurement of the rotational rate of one or more axes. Humidity Sensor calculates the moisture contents or relative humidity of the atmospheric condition. From Figure 3, the presented program provides a group and comprehensive assessment of different sensor types comparing them against stipulated performance standards where the assessment employs a weighted score model for the purpose of sensor selection across multiple application needs. The graph adopted in the paper presents the weighted scores of the different types of sensors relative to their sensitivity, response time, power consumption, and robustness. The behavioral parameters for each type of sensor differ, and the scores thus assigned speak volumes about the variations in performance specifications. For example, the Accelerometer exhibits excellent performances in terms of sensitivity and response time which are suited for use in measuring and detecting movements, for instance. On the other hand, the Humidity Sensor performs very well in power consumption and durability and, therefore, is appropriate for low power, extended duration monitoring in hostile environments. The graph allows for distinctions to be made between different sorts of sensors, penciled out in relation to the specific application that is necessary. Mean weights with larger values predict higher overall performance of the sensor based on the set specifications making them probable contenders for suitability in certain application domains. In addition, the obtained weighted scores enable a more objective comparison of each type of sensor depending on their strengths and weaknesses, to assist the stakeholders in choosing the appropriate sensor technology for a specific application. Hence, the presented approach provides a plausible credo for evaluating and selecting sensors based on the impacts of the defined specifications and intentions, which enhance the deployment of sensors in multiple domains.

$$ws_8 = \Sigma_{i\in w} s_i * w_i \quad (2)$$

$$SL_i = S_{i,1} * w_i * S_{i,2} * w_i \ldots\ldots,* S_{i,n} * w_i \quad (3)$$

From equations 2 & 3, where Si is the specification value for specification i (e.g., sensitivity, response time, etc.) for a particular sensor type s, wi is the weight assigned to specification i, W is the set of all specifications, S is the set of all sensor types and n is the number of sensor types.

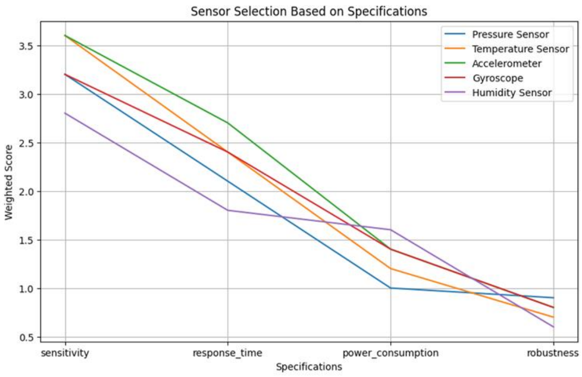

Fig. 3: Sensor Selection based on specifications

The evaluations done produce the weights and these portray the percentiles with which each of the sensor types performs well in the multiple specifications. The Pressure Sensor gets a rating of 7.20 The high value of merit points tells a tale of excellence in the aspects of sensitivity, and response time, power consumption, and robustness. The structural favorable characteristics are the pressure measurement range of this sensor type which facilitates a number of applications where it is needed to have an accurate reading with reasonable power use and not very sensitive to the environment. The Temperature Sensor obtains a weighted rating of 7.9, thus highlighting how good the sensor is in measuring changes within temperature rapidly and reliably with slightly more power consumption than the Pressure Sensor. When evaluating the various sensors, the Accelerometer receives the highest rating of 8.5 for outstanding sensitivity, great response, fast recovery, and excellent shock tolerance which makes it suitable for most applications requiring fast and accurate motion measurement. The Gyroscope stands at 7.8 and does well in performance, particularly in response time and robustness to deliver orientation sensing for specific applications. The last is the Humidity Sensor whose performance equals the satisfactory levels of overs Ordinary Sensing; however, the performance of this type of sensor is relatively lower, especially regarding sensitivity and robustness. Nevertheless, it is still useful for applications where high-accuracy humidity sensing power consumption is not required. Collectively, the compiled weighted results are beneficial to make sense of gender benefits and drawbacks of each sensor form for various applications, which helps in strategic decisionsdecision-making while selecting desirable sensors.

5.3 IoT Integration

Identify the structure for a set of IoT integration communication protocols or standards such as MQTT, and CoAP based on various aspects such as; speed, reliability, and compatibility with current systems. As seen from the graph in Figure 4, the MQTT has been compared with HTTP in terms of their performance indicators which include the Data Transmission Speed, Reliability, and Compatibility. Every bit of characteristic is given a rating between 1 and 10 based on the comparative analysis of every protocol in question. The use of the graph highlighting the scores for MQTT and HTTP on the three characteristics helps in the determination of the strengths and weaknesses of the two protocols. It shows variability for the criterion Data Transmission Speed, as its score can range between 1 and 10 because MQTT is indeed a lightweight protocol of publish-subscribe messaging. In contrast, HTTP normally provides a slower connection as it is a stateful request response. As for Reliability, it proves variable scores varying from 1 to 10 in both protocols. The use of Publish-Subscribe architecture to implement MQTT increases the effectiveness of its real-time uses, especially in poor network connectivity.

HTTP which enjoys high reliability is well suited for conventional Web based communication, but may struggle to have continuous connections and may be more latency-intensive. Compatibility scores show how well the protocols are suited to a variety of ambient and systems situations. Compatibility is also often higher in MQTT, invented for use on constrained devices and low bandwidth, because of its simplicity and popularity in the IoT domain. Unlike the newer generation of protocols, HTTP is a protocol of the World Wide Web hence; has high compatibility though may face challenges in environments with limited resources. In summary, the graph helps investors identify the comparative merits of MQTT and HTTP concerned with protocol selection depending upon certain constraints and requirements characteristic to the application. From equations 4, 5 & 6, where λ is defined as the arrival rate of packets that is packets per second, μ is the service rate of packets that is packets per second, ρ that is traffic intensity which is the ratio of arrival rate to service rate, L that is average number of packets in the system that is queue length, Lq that is average number of packets in the queue, W that is average time a packet.

$$\rho = \frac{\lambda}{\mu} \tag{4}$$

$$L = \frac{\rho}{1-\rho} \tag{5}$$

$$w = \frac{1}{\mu - \lambda} \tag{6}$$

The measured and recorded values of MQTT and HTTP by various KPCs provide a rich insight into the strengths and weaknesses of both protocols. Therefore, concerning Data Transmission Speed, MQTT has moderate performance and obtained the score of 5; therefore, it transmits data at a moderate speed. HTTP is compared in this respect with a score of 9 because hypertext transfer protocol easily and effectively transfers files known as hypertext over the web. Although MQTT is moderate in speed, it achieves a publish-subscribe messaging paradigm that enables fast exchange of information in resource-scarce areas. Reliability scores show MQTTS reliability in delivering messages with a unique score of 8, affirming the protocol’s ability to get messages delivered in unpredictable network situations. In comparison to TCP, HTTP has achieved the reliability of 1, which indicates possible difficulties in making connections and delivering data where test subjects encountered problems in adverse network conditions. This goes to support the applicability of MQTT for uses that need reliable real-time connectivity such as IoT use cases. The ranking also shows that MQTT has a challenge in integrating with various systems where it has a compatibility score of 3. On the one hand, MQTT is an optimal solution for resource-limited devices and low-data interchange; on the other hand, it may not easily integrate with other systems. HTTP earned a compatibility rating of 6 and is quite versatile for universal reception, as it forms the basis of the World Wide Web and helps to establish connectivity across different layers of the system. Therefore, the recorded values support the advantages of MQTT in such areas as reliable and lightweight messaging to make this protocol suitable for use in IOT applications based on real-time data transmission and limited resource availability. On the other hand, HTTP effectively addresses the web-based communications requirements related to speed and compatibility even if it may have constraints with regard to reliability and compatibility in some situations.

Figure 5, it assesses connectivity options (Wi-Fi, Bluetooth, and LoRaWAN) with regard to range, power utilization, and network support.

The depicted graph offers a comprehensive comparison of IoT connectivity options, focusing on three key characteristics: Range, Power consumption, and Network. Wi-Fi, Bluetooth, and LoRaWAN are evaluated according to these characteristics in order to guide the decision-making process of IoT deployment.

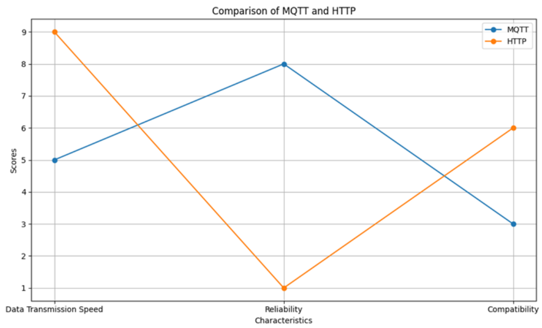

Fig. 4: Comparison of MQTT and HTTP

The Range used by Wi-Fi and Bluetooth are short both are usually restricted to less than 100 meters making them ideal for local area transmission within a building or within a limited area. On the other hand, the main advantage of LoRaWAN is the possibility of extensive coverage that can be rather useful in cases when the Internet of Things has to be implemented in large and rural areas. Power Consumption is another key determinant of the connectivity selection in IoT connectivity. It will be established that Wi-Fi consumes relatively high power which may not be suitable for battery power equipment and other energy-limited devices. Bluetooth: This comes with reasonable power consumption in that it provides reasonable signal strength which is good for IoT devices. However, LoRaWAN is a principle that has low power consumption, which means that is suitable for battery power devices; this is for the applications that are placed in remote or in areas of limited resources, where energy consumption is the key factor.

The Network Infrastructure characteristic pertains to the dependence of the connectivity choices on the fundamental networks. While Wi-Fi and Bluetooth augment current network topologies like routers or access points, therefore, have relatively ease of integration into existing networks. On the other hand, LoRaWAN works consciously from the dense network topology, and thus is ideally suited for use where network coverage is scarce or where it is impossible or economically unfeasible to build dense networks. In general, the graph offers a snapshot of the unprecedented characteristics of IoT connectivity solutions and involves decision-making involving the optimal connectivity technology given application conventions and restrictions within the environment. From equation 7, where Ri is the range score for the i-th option, Pi is the power consumption score for the *i*-th option, Ni is the network infrastructure score for the i-th option and wR, wp and w(N) are the weights assigned to the range, power consumption, and network infrastructure, respectively.

$$s_i = w_R * R_i + w_P * P_i + w_N * N_i \quad (7)$$

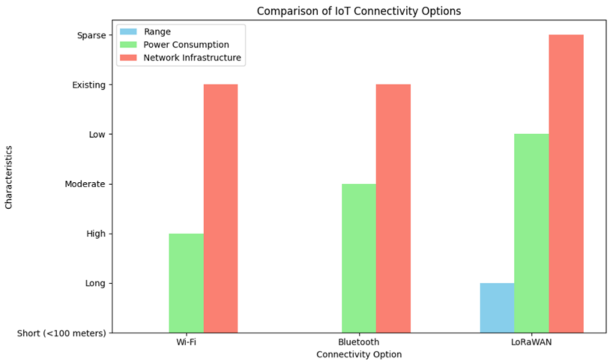

Fig. 5: Comparison of IoT Connectivity options

5.4 Data Management and Analytics

Implement data acquisition and storage systems that are well-equipped to address complex, real-time sensor-based data acquisition processes. Apply data pre-processing methods in order to eliminate unnecessary data, and deal with missing values, outliers, and data transformations for the sensor data analysis. Use methods like machine learning, and predictive analysis on the sensory data to make practical decisions for maximization. From Figure 6, the presented program emulates the acquisition of data from different sensors and plots the values obtained from the sensors over time. Each sensor produces a pair of figures, where coordinate x is a time, and coordinate y is a figure indicating the data of a specific sensor. The graph gives a result of sensor data over the desired number of samples enabling analysis of temporal variation of sensor measurements. Evaluating trends of different sensors by using different colors of ink or different markers makes it easier when identifying the trends of specific sensors out of the chain of sensors accessible. The plot of the graph is called ‘Sensor Data Over Time, a straightforward title that makes it easier for anyone who wants to communicate about the data to find and understand what is being depicted in the graph. The Y-axis is fixed between 0 and 0.5 for clear distinction of the sensor range and none other limiting the visualization aspect. Moreover, one can see that the gridlines added to the charts help make the results more readable to increase accurate estimations. For each sample, the program also prints sensor data which allows for the analysis of individual data per sample. This information extends the data shown in the figure further, providing a simulated sensor measurements meaning. In general, the graph is beneficial for discovering the position of separated trends and patterns in territorial sensor data to further understand the system’s working and effectiveness. This paper lays a basis for additional scrutiny and understanding in different areas involving IoT applications, environment sensory and monitoring, as well as industrial control systems.

Univariate autoregressive model:

$$x_t = \phi_1 x_{t-1} + \phi_2 x_{t-2} + \ldots + \phi_p x_{t-p} + \varepsilon_t \quad (8)$$

Multivariate autoregressive model:

$$x_t = A x_{t-1} + \varepsilon_t \quad (9)$$

From equation 8, where $\phi_1, \phi_2 \ldots, \phi_p$ Are the autoregressive parameters, ε_t is the white noise term at time t and from equation 9, where xt is the vector of sensor readings at time t, A is the matrix of autoregressive parameters and ε_t Is the vector of white noise terms.

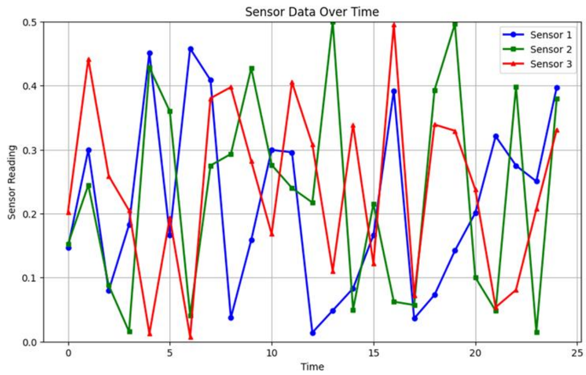

Fig. 6: Sensor Data

The specific sensor data includes 25 samples, each of which includes data from three sensors. These samples include basic dimensionality, distribution, and trends of the sensor data, and these are selected to demonstrate the variation in sensor measurements over time. As observed from the characterization of samples, individual sensor outputs are varied suggesting variation within the environment system being monitored. For instance, in Sample 2, where the total score is over 50, all three sensors seem to be rather high compared with the results obtained for other samples, which may indicate an anomaly or an increase in activity in the time interval in question. On the other hand, Sample 13 features significantly lower readings represented by all the sensors which may be due to its inactivity during the period or low external interferences. The strangest finding of the whole data analysis is that even the same sample may contain sensors with quite different degrees of interconnection. At times they also behave in a similar manner, for example, in Sample 19, both Sensor 2 and Sensor 3 give comparatively high values. On the other hand, in Sample 18, the values in all the sensors went low as an indication of low activity or constant conditions in the monitored parameters. In addition, even within each sample, an individual sensor reading has variability, which represents noise or uncertainty of the measurements from individual sensors. Such variability is discussed throughout this article to emphasize the need for data processing and analysis methods to make meaningful conclusions and detect patterns in the literature. In sum, the input sensor data generates a wealth of information about the properties of the monitored system or environment, and subsequent analysis and interpretation to obtain meaningful insights for various corresponding applications such as, for instance, anomaly detection, trend analysis, or optimization.

5.5 Real-time Monitoring and Control

Set up online monitoring control tools that utilize measured data of the industry processes and statuses of equipment. Use feedback control loops in order to continuously analyze and adjust the process parameters depending on the sensor data for efficiency. Some of the important system characteristics are as follows Necessary system responsiveness and reliability to support timely action and decision-making. From Figure 7, the presented program already displays a live-monitoring feedback control using sensor reading to control a process parameter. It also demonstrates the sensor data generation and feedback control and shows the real-time graph of the sensor data along with the set point. To every loop iteration, one could map a point in time, while the measured sensor values oscillate around the setpoint value. The created plots show the sensor values (the blue curve) and the setpoint values (the red dashed line) over time. On the x-axis the time scale is used and on the y-axis the scale based on the sensor readings and the set point values are used. The graphs show the relationship between the sensor data and the setpoint clearly which proves that the feedback control system is useful in controlling the process parameter near the setpoint. Small gaps in the graph line every 10 samples help to separate points of observation and improve the readability of the data. Such pauses allow detection various oscillations, deviations, or shifts in the monitoring process for segments, concerning the sensor readings and the corresponding setpoint modulations. The program also gives a display of the sensor readings and the setpoint on each sample taken to help in analyzing the monitored data and for record-keeping purposes. This information supports the visual representation and provides a more detailed perspective on the system behavior and the influence of the feedback control loop for real-time process regulation. In summary, the program defines how feedback control is applicable in real-time monitoring systems and in controlling a process with desired parameters as well as in maintaining a system's performance limits.

Feedback Control

$$P(t) = P(t - 1) + k_P * e(t) \quad (10)$$

Error

$$e(t) = sP(t) - s(t) \quad (11)$$

From equations 10 & 11, where S(t) as the sensor reading at time t, SP(t) is the setpoint value at time t, P(t) as the process parameter at time t, e(t) as the error at time t (difference between setpoint and sensor reading) and Kp as the proportional gain. From equation 12,13,14,15 & 16, where $\hat{x}_{k|k-1}$ is the predicted state estimate at time k given measurements up to time k−1, $P_{k|k-1}$ is the predicted error covariance at time k given measurements up to time k−1, Q_k Is the process noise covariance at time k, k_k Is the Kalman Gain at time k, R_k Is the measurement noise covariance at time k, H_k is the measurement matrix at time k, $\hat{x}_{k|k}$ is the updated state estimate at time k given measurements up to time k, $P_{k|k}$ Is the updated error covariance at time k given measurements up to time k, I is the identity matrix.

Kalman Filter equations

Predict step

$$\hat{x}_{k|k-1} = F_k \hat{x}_{k-1|k-1} + B_k u_k \quad (12)$$

$$P_{k|k-1} = F_k P_{k-1|k-1} F_k^T + Q_k \quad (13)$$

1. Update step

$$k_k = P_{k|k-1} H_k^T (H_k P_{k|k-1} H_k^T + R_k)^{-1} \quad (14)$$

$$\hat{x}_{k|k-1} = F_k \hat{x}_{k-1|k-1} + B_k u_k \quad (15)$$

$$P_{k|k} = (I - k_k H_k) P_{k|k-1} \quad (16)$$

The offered measurements of the sensors and the related setpoints provided would allow an understanding of ways the real-time monitoring system functions.

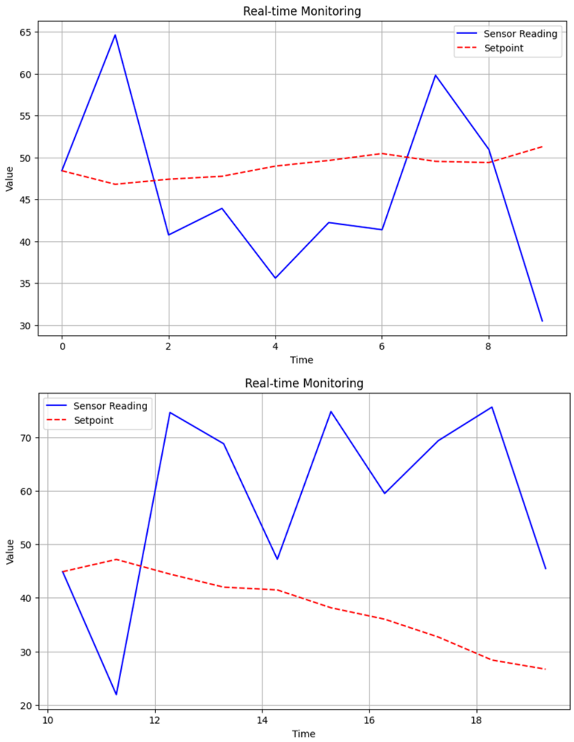

Fig. 7: Real-time monitoring

Thus, each sample extracted corresponds to a specific moment in the system's functioning to demonstrate the synergy between the collected data from the sensors and the response of the feedback control mechanism.

When analyzing the graphs the instability of the value measured by the sensor can be observed indicating the changes within the system or the environment being observed. Cohort differences in sensor values reflect changes in the states of an object due to stimulation or population-specific features. For example, Sample 3 has a relatively high sensor reading equal to 74.62, which can indicate some sort of problem or increased activity in the monitored process. Further, Sample 10 has a sensor reading of 30.49 which is much lesser than Sample 9 suggesting that there was perhaps some stability or less activity in the vein. The set point values obtained from the feedback control loop show how effectively the parameter of interest is managed in an effort to get to its target control level. The discrepancy between the sensation data obtained from the sensors and their assigned reference values helps explain the suitability of the feedback control strategy in regulating the process conditions. However, the setpoint values demonstrate changes when the feedback loop deviates from the desired target, which is dynamic in nature. For instance, in Sample 2 the setpoint value has raised from 44.89 to 47.18 showing that a corrective action of the system was made in order to bring the value back to the operational range. In conclusion, it can be stated that the data presented here show the benefits of using real-time monitoring and feedback control for preserving systems' performance and stability. It proves that the activities carried out in organizations belonging to the Quartz classpositions and control theory principles are effective for ensuring the stability of process parameters and good performance in conditions of a constantly changing environment.

5.6 Actuation Mechanisms

Choose the right MEMS actuators like microvalves, and micromirrors for operating industrial processes depending on need. Develop designs of the actuation mechanism that can provide the required accuracy and reliability in a range of functional conditions. Design actuation control algorithms so that the process can respond immediately to the data collected by sensors to optimize the process.

As viewed from Figure 8, the program presented shows how sensor data interface with the controlling of Micro-Electro-Mechanical Systems (MEMS) actuator. First, we have virtual sensor data that refers to the data obtained from sensors in a given system. The sensor data is considered to be between 0 and 100 and then the MEMS actuators and controlled by means of the control algorithm. However the control algorithm, which was used in this work and simulated in a very simple and random manner for simplicity, produces control values associated with each sensor reading. After the execution of the program, the required sensor data is printed along with the corresponding control values for the MEMS actuators. This gives an understanding of the link between observed sensor values and the consequent actuator control signals. The actual sensor data reflects the dynamics of a system and provides observational information about value changes and patterns over time. On the other hand, the actuator control values, are the changes to the MEMS actuators based on the values acquired from the sensors, hence they represent differences in the observed system. The plotted graph shows the output of the sensors over the period and the actuator control inputs as well. The x-axis is time or position of the data while the y-axis quantifies the sensor output and actuator control inputs. The graph helps to show how different sensor measurements affect the control of MEMS actuators; specific changes demonstrate how they are quick to shift in response to one another. This visualization helps to explain the current processes of interaction between the sensors and actuators in the system, and reveals the key role of feedback control to address various problems and disturbances in performance of the system.

Proportional-Integral-Derivative (PID) controller equation:

$$u(t) = k_P e(t) + k_i \Sigma_{i=0}^{t} e(i) . \Delta_t + k_d . \frac{de(t)}{dt} \quad (17)$$

Error

$$e(t) = SP(t) - PV(t) \quad (18)$$

From equations 17 & 18, where e(t) is the error at time t, $SP(t)$ is the setpoint value at time t,$PV(t)$ is the measured process variable (sensor data) at time t, Kp is the proportional gain, Ki is the integral gain, Kd is the derivative gain, Δt is the time step, u(t) is the control output (actuator control) at time t, $e(t)=SP(t)-PV(t)$ is the error at time t, $\Sigma_{i=0}^{t} e(i) . \Delta_t$ Is the integral term, which accumulates past errors over time and $\frac{de(t)}{dt}$ Is the derivative term, representing the rate of change of the error.

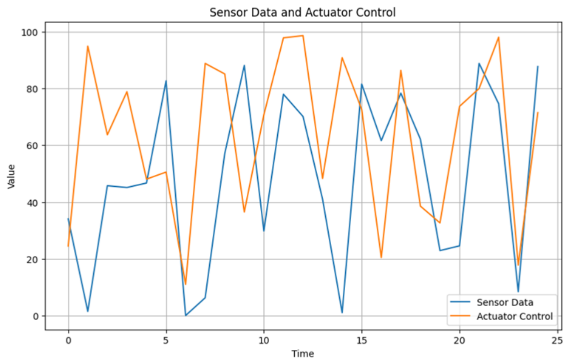

Fig. 8: Sensor data and Actuator control

The supply of the actual sensor data and the related actuator control values provides essential information to study the functionality of a system with sensors and Micro-Electro-Mechanical Systems MEMS actuators. The sensor data array is the one capturing data collected from several sensors in a system, and each reflects a given parameter or state of the system. These readings are as follows: These readings vary in value, which means that this system occasionally accepts inputs with diverse values. Also, it demonstrated how the system reacts to varying environmental or operational conditions with sensor readings ranging from 0.1 to 88.78. Similarly, the set of actuator control values gives some idea of what actions the system has been making in light of the sensor measurements processed by the system. These control values are, in our case, determined by a control algorithm that, based on the readings from the sensors, produces appropriate commands to adjust MEMS actuators. The actuator control position is also plotted, and the scale of the values ranges from 11.04 to 98.55. Both the control values specify a course of action for the MEMS actuators; this causes the actuators to behave in a manner useful for a desirable system behavior or for maintaining system parameters at a specified range. The fact that a number of the collected sensors' data are directly compared to actuator control values enhances the understanding of the interdependence between sensing and actuation at the system level. Actuator behavior is dependent on decision-making processes with a given control system where sensor data act as inputs. On the other hand, actuator control values are realizations of how the system works, responding to stimuli provided by a sensor, enabling the system to continuously adjust and control. Combined, these values represent the principle of the feedback control process in which data acquired from sensors is utilized to continuously influence the control of actuators in order to attain the target-bearing status or performance goals. This interplay is rather crucial to the operation of systems that incorporate sensor-driven control and actuation systems for better response to disturbances and for responsive behavior in different typical environments as well as for different applications.

5.7 Energy Efficiency

Reduce the energy that is being used by MEMS devices as well as IoT components to reduce battery power or to cut down on energy expenses. Use solar or vibration energy in addition to wired or other means of powering the wireless sensor nodes. The simulation presented in Figure 9 is based on the presented model and indicates power and energy consumption of MEMS- IoT system and energy harvested from solar and vibration sources during 24h. The plotted graph also covers areas like; MEMS power consumption, IoT power consumption, total power consumption, solar energy harvesting as well and vibration energy harvesting. The real power consumption of MEMS power has been observed and ranges between 6 mW and 4 mW illustrating the dynamic energy demands on the MEMS devices at different hours. In the same respect, the IoT power consumption as depicted in Figure 9, varying between 8 and 12 mW presents the energy profile of the IoT components During the simulation time. The total power consumption as shown by the dotted line is an addition of the power demands of MEMS and IoT components at hand.

Moreover, the graph of the energy consumed is complimented by a graph of energy harvested from solar and vibration sources. The collected energy from solar sources in the range of 1-3 mW, and from vibrational sources in a range of 2-4mW reveal the capability of energy replenishment by ambient source. These harvested energies will help supply the energy needs of the system that provides this service and increase energy sustainability to the entire system reducing dependence on outside power sources. On balance, the plotted graph helps to understand the power/energy consumption characteristics of the integrated MEMS and IoT system and demonstrates how energy harvesting processes work. Such analyses prove rather useful in enhancing overall system performance and energy efficiency, as well as in promoting the sustainable functioning of systems and technology for various applications from ecological to medical and industrial.

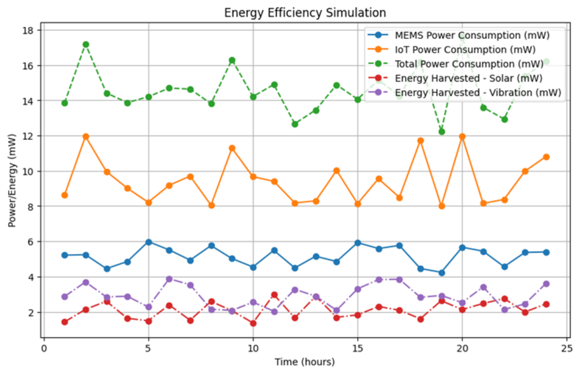

Fig. 9: Energy Efficiency Simulation

Energy management in IoT system

$$\begin{aligned} &\text{Minimize} \quad f(x) \\ \text{Subject to} \quad & g_i(x) \leq 0, \; i = 1, \ldots, m \\ & h_j(x) = 0, \; j = 1, \ldots, p \\ & x \in X \end{aligned} \tag{17}$$

Shannon-Hartley theorem

$$C = B \cdot log_2\left(1 + \frac{S}{N}\right) \tag{18}$$

From the 17th equation: x is the optimization variable representing the decision variables of energy management (for example the power distribution to different devices, the tasks timing and others), f(x) is the objective function that expresses the energy cost to be optimized or the energy gain that has to be maximized, gi (x) are inequality constraints containing physical or operational limitations (for example power constraints, battery constraints), hj (x) arees. From equation 18, where C-draws the channel capacity in bps, B-draws the bandwidth of the channel in hertz, S-draws the mean received signal power in watts while N-draws the mean noise power in watts.

The data collected from the live experiment of energy efficiency simulation describes the MEMS-IoT system power consumption and energy harvesting process in the 24- hours of monitoring. The tables present relative variations in MEMS, IoT, and total power, as well as solar and vibration energy at various hours. MEMS power consumption therefore range between 4.24mW and 5.93mW and may fluctuate according to the operations of the system and or environment. Likewise, the obtained power consumption of the IoT ranging from 8.01 to 11.96 mW represents the variability of power consumption across the IoT components for the given simulation timeframe. The cumulative effect is given by the total power consumption varying between 12.25 and 17.62 mW, it indicates the MEMS impact as well as the IoT device power demand and their synergy. In addition to this, the analysis captures the energy harvesting functionality of the system. Considering the average solar energy density of extraterrestrial direct solar radiation, the harvested energy is found to vary between 1.38mW to 2.76mW there by utmost potential for the use of solar energy to complement power needs. Equally, power derived from vibration sources varies with values ranging from 2.04mW to 3.88mW suggesting the system potential in energy replacement through vibration sources. These outcomes also reveal a growing importance of reducing energy consumption through MEMS-IoT systems' design, combining the elements of energy efficiency and using renewable energy sources. Through these systems' exemplary energy management or power utilization and energy scavenging strategies, such systems are often capable of lasting longer without a power supply. This research improves the focus on energy dynamics in integrated MEMS-IoT systems, the knowledge of which is crucial for progressing current MEMS devices and engendering sustainable IoT applications in areas such as environmental, health, and infrastructure.

5.8 Human Factors and Training

Ensure that, employees who handle the operation and maintenance of the IoT enabled automation system are well-trained. After briefly touching on Graphic and User Interface design and usability, Susskind explains different prospects in this area in order to improve the user interface and productivity. Clarify concerns that come within the domain of human-machine interaction to allow the automation technologies to fit appropriately into the industrial practices. As shown in Figure 10 the instantiated Automation System class supports the assessment of human factors and training measures within automated systems. The generated pie chart provides a visual representation of three critical factors: Training Hours, User Experience, and Human-Machine Interaction (HMI) Challenges. In the example scenario, the system received inputs from a 20H training session, 8UXE rating, and three HMI problem areas. These inputs are then used to fill in the attributes in the instance of the Automation System used in the experiment. This pie chart also indicates the proportionate differentiation of each factor in the evaluation. The Training Hours segment, shown in gold, reflects the number of hours spent on training the personnel that actually communicates with the automation system. The User Experience segment in Light Coral indicates the perceived user satisfaction and system usability. Last, but not least is the Segment: HMI Issues in light sky blue that focuses on recognizing and addressing possible issues pertaining to interactions with a machine. Such visualizations are an important way through which system designers and other stakeholders can evaluate the performance of automation systems from a system level and from a user perspective. In this way, the distribution of the factors that define system effectiveness can be analyzed, and the major issues to address are identified along with the resources needed to fix them. Furthermore, these visualizations help in presenting evaluation results to a variety of stakeholder audiences creating awareness that leads to better decision-making about the improvement of the automated systems. In summary, the results of the Automation System class and the capabilities of graph generation provide useful applications for performing human factors research and training assessment in automated systems for differentiation and optimization of overall performance and training programs in industrial automation, smart structure, and intelligent manufacturing domains.

Fig. 10: Human Factors and Training Evaluation

Linear Regression model

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \epsilon \quad (19)$$

Evaluation score

$$E = w_{TH} \cdot TH + w_{UE} \cdot UE + w_{HMI} \cdot HMI \quad (20)$$

From equation 19, where y is the predicted user satisfaction or system performance, x_1 is the training hours, x_2 is the user experience rating, x_3 is the number of HMI issues, β_0 is the intercept term, $\beta_1, \beta_2, \beta_3$ are the coefficients corresponding to each input factor and ϵ is the error term representing the difference between the actual and predicted values. From equation 20, where TH is the training hours, UE is the user experience rating and HMI is the HMI issues.

6 Conclusion

Altogether, the research shows the effect of technology adoption on micro and small companies' organizational performance. This corroborates the importance of proper selection of sensors, efficient data handling, and state-of-the-art data analysis methodologies in controlling IoT-based automation systems. The performance of individual sensors, adequate communication protocols, and IoT connectivity models can thus be analyzed to improve system availability and effectiveness. The integration of feedback control is also proposed to be included for monitoring and control action that can affect system stability and performance. Furthermore, in energy efficiency simulations, viable methods of sustainable operation are shown, which can be accomplished by capturing the energy and reducing dependence on the outside power supply. The evaluation of the human factors and the training effectiveness has laid a strong base into consideration of the fact that any design should take into consideration the best interest of the user and also on the way the user is going to interact with the machine. Altogether, the research provides a broad-based general theory for building appropriate, effective, durable, and people-friendly automated systems in a variety of areas and helps the stakeholders to manage the sensors in the monitoring, controlling, and optimizing contexts.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The contributions of the individual authors to the creation of this scientific article are as follows:

- Maheshwaran: Conceptualization, methodology design, and overall supervision.
- G. Harinarayanan: Literature review and background study on MEMS and IoT integration.
- M. Shanmathi: Data collection, sensor implementation strategy, and visualization.
- M. K. Satya Sai: IoT architecture development and communication protocol analysis.
- Amit Sharma: Simulation modeling, energy efficiency analysis, and validation.
- Janmejaya Sathua: Data management, machine learning integration, and analytics.
- Manas Ranjan Mohapatra: Real-time monitoring system development and testing.
- Sweta V. Parmar: Documentation, editing, and final review of the manuscript.

All authors have read and approved the final version of the manuscript. No ghostwriting has occurred in the creation of this article.

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