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REVIEW

Bridging the Gap: IoT and Robotics for Seamless Automation in Aerospace

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ABSTRACT: This paper explores the rapidly evolving fields of Robotics and the Internet of Things (IoT), highlighting their key components, technological advancements, levels of autonomy, control systems, and their integration. Robotics contributes to modern industries by enhancing efficiency, precision, and automation. A comprehensive examination is conducted to highlight the convergence of IoT and robotics, particularly their applications in aerospace and other innovative domains, to develop a fundamental understanding of how these systems perform real-time input correction and autonomous decision-making. Additionally, the paper analyzes market trends from 2023 to 2024 and forecasts growth until 2034, emphasizing key drivers such as artificial intelligence integration, edge computing, and industrial automation. The study concludes by discussing how robotics, in conjunction with IoT and aerospace technologies, is shaping the future of technology through practical implementations and recent advancements in sensor networks, distributed intelligence, and adaptive control systems, along with their applications across various domains. By highlighting the potential of IoT-enabled robotic systems, particularly in aerospace missions, this work aims to stimulate further research and innovation in this emerging field.

KEYWORDS: IoT; robotics; rovers; aerospace; internet of robotic things (IoRT)

1 Introduction

Robotics became visible in the guise of a transformative field that brought engineering fields like computer science and advanced technologies to design machines with the potential to execute tasks independently or without human interference. Over the past decade, advancements in artificial intelligence (AI), machine learning, and IoT have significantly enhanced the competency of robotic systems, authorizing them to operate with a great extent of intelligence & efficiency.

The rapid advancement of digital technologies has significantly transformed modern industrial and scientific domains, with the Internet of Things (IoT) and robotics emerging as two of the most influential innovations. IoT enables seamless connectivity between devices, sensors, and systems, facilitating real-time data acquisition, communication, and intelligent decision-making. Concurrently, robotics has evolved from simple programmable machines to highly autonomous systems capable of performing complex tasks with precision and efficiency. The integration of these two domains has given rise to the concept of the Internet of Robotic Things (IoRT), which represents a paradigm shift toward intelligent, interconnected, and adaptive robotic ecosystems.

In the aerospace sector, where precision, safety, and efficiency are of paramount importance, the adoption of IoT-enabled robotic systems has shown tremendous potential. Applications such as satellite maintenance, planetary exploration, unmanned aerial vehicles (UAVs), and automated manufacturing processes increasingly rely on advanced robotic systems integrated with real-time data analytics. These technologies not only enhance operational efficiency but also reduce human intervention in hazardous environments, thereby improving safety and mission success rates.

Despite these advancements, several critical challenges hinder the seamless integration of IoT and robotics in aerospace applications. One of the primary issues is the lack of efficient real-time communication and coordination among distributed robotic systems operating in dynamic and often unpredictable environments. Additionally, latency, bandwidth constraints, and data security concerns pose significant obstacles to ensuring reliable data transmission between IoT devices and robotic platforms. The heterogeneity of devices and protocols further complicates system interoperability, making it difficult to achieve standardized and scalable solutions. Moreover, existing robotic systems often lack sufficient autonomy and adaptability to respond effectively to rapidly changing conditions, particularly in remote or space environments where human intervention is limited.

To address these challenges, this paper explores the integration of IoT and robotics through the IoRT framework as a potential solution for achieving seamless automation in aerospace systems. The proposed approach emphasizes the use of intelligent communication architectures, edge and cloud computing, and AI-driven decision-making mechanisms to enhance system responsiveness, reliability, and scalability. By enabling real-time data processing and decentralized control, IoRT-based systems can significantly reduce latency and improve coordination among multiple robotic agents. Furthermore, the incorporation of advanced security protocols ensures safe and trustworthy data exchange across interconnected networks.

This review paper aims to provide a comprehensive analysis of the evolution of IoT and robotics, their convergence into IoRT, and their applications in the aerospace domain. It also identifies key challenges and discusses emerging solutions that can facilitate the development of robust, efficient, and intelligent robotic systems. Ultimately, the study highlights the potential of IoRT to bridge existing technological gaps and pave the way for next-generation automation in aerospace and beyond.

2 Background

This section covers various aspects of IoT and Robotics. The integration of the Internet of Things (IoT) and robotics is based on fundamental concepts from distributed systems, control theory, and artificial intelligence, enabling the development of intelligent and interconnected systems. IoT facilitates real-time data collection and communication through sensor-enabled devices, supported by wireless protocols and cloud–edge computing architectures, while robotics relies on sensing, actuation, and adaptive control mechanisms to perform autonomous tasks. The convergence of these domains has led to the emergence of the Internet of Robotic Things (IoRT), which is grounded in the framework of cyber-physical systems, where physical processes are tightly integrated with computational and networking components. This integration enables real-time monitoring, decision-making, and coordinated actions among multiple robotic agents. Additionally, advancements in machine learning enhance system adaptability and efficiency, while considerations such as interoperability, scalability, and data security play a crucial role in ensuring reliable system performance, particularly in complex environments such as aerospace applications.

2.1 Internet of Things (IoT)

The term IoT is an abbreviation of the phrase "Internet of Things." The first term in the phrase, "Internet," refers to a global system of interconnected computer networks based on standard Internet protocols (TCP/IP), which is used by millions and billions of users worldwide [1]. The network contains millions of public, government, private, business, and academic networks of local and global scope, comprising a broad array of electronic systems linked through wireless and optical networking technologies [2]. The second word, "Things," refers to the devices and systems that are connected and able to communicate and interact without significant human intervention. Connection to the Internet and data collection through sensors enable the "Internet of Things" to function concurrently [1].

The Internet of Things (IoT) is an infrastructure of interconnected entities, as shown in Table 1, consisting of components that collect, transmit, process, and act on data. Sensors gather environmental data, which is transmitted through networks such as Wi-Fi or 5G to cloud platforms for storage and processing. The data is analyzed using techniques such as AI and machine learning to generate insights. Users interact with the system through applications or dashboards, while security mechanisms protect the data. Finally, actuators execute actions based on the processed information, enabling automation and intelligent system response.

Table 1: Components of IoT.

S. No.	Components	Function	Examples
1.	Devices and Sensors	Collects the data from the environment.	Smart thermostats, fitness trackers, RFID tags, surveillance cameras.
2.	Network	Provides means for devices to communicate with each other and with central servers.	Wi-Fi, Bluetooth, Zigbee, 5G, LoRaWAN, Ethernet.
3.	IoT Platforms and Cloud Services	Acts as the intermediary between devices and applications, providing data storage, processing, and management capabilities. The cloud ensures scalability and remote access.	Microsoft Azure IoT hub, Google Cloud IoT, AWS IoT.
4.	Data processing & Analytics	Processes raw data collected by devices to generate actionable insights, using Artificial intelligence with machine learning for advanced analytics.	Real-time traffic monitoring system processing GPS data to optimize routes.
5.	User Interface	Enables users to link with the IoT system, monitor performance with control devices through dashboards, mobile apps, or web portals.	A smartphone app to control smart home devices like lights and thermostats.
6.	Security and Privacy	Ensures data integrity, confidentiality, and protection from unauthorized access through encryption, authentication protocols, and secure communication.	End-to-end encryption in smart home networks and multi-factor authentication.
7.	Actuators	Devices that cause the system to execute actions on the basis of input received by sensors and control systems.	Motors that open smart windows or valves that control water flow in irrigation systems.

IoT is a global network that enables interactions between human-to-human, human-to-thing, and thing-to-thing communication [2]. Sensors and actuators are physical objects embedded in systems, ranging from pacemakers to roadways, and are linked through wired or wireless connections, often operating on IP addresses that connect them to the network [3]. IoT represents a world in which physical objects are connected within a system, allowing information to be shared and accessed accordingly [4].

2.1.1 Communication Protocols in IoT

It is crucial to understand the communication protocols IoT uses in the layers of the network, each serving specific purposes. Hence, the breakdown of key protocols is as follows:

Physical and Data Link Layer Protocols (Short-range): Several wireless communication protocols support various IoT applications based on range, power consumption, and data needs. Bluetooth Low Energy (BLE) is ideal for battery-powered, short-range devices like wearables and smart home gadgets. Zigbee is widely used in industrial control and home automation, offering low power consumption and mesh networking. Z-Wave is another reliable, low-power mesh protocol, mainly used for home automation. Wi-Fi suits IoT devices requiring high bandwidth, such as real-time cameras. Near Field Communication (NFC) enables very short-range communication and is commonly used in contactless payments and access control. RFID uses electromagnetic fields to identify and track tagged objects, making it valuable in supply chain management, asset tracking, and access control.

Network Layer Protocols (Long-range): LoRaWAN is ideal for low-power, long-range IoT applications such as agriculture and environmental monitoring. Cellular networks (LTE, 5G) provide wide-area connectivity, making them suitable for mobile and long-distance IoT use cases such as transportation and smart cities.

Transport Layer Protocols: TCP is used for reliable, connection-based communication where data accuracy is critical, while UDP offers faster, low-latency communication suitable for applications where speed is more important than reliability.

Application Layer Protocols: Various communication protocols support IoT data exchange based on efficiency, reliability, and performance needs. MQTT is a lightweight, publish–subscribe messaging protocol widely used in IoT for its scalability and efficiency. CoAP is designed for resource-constrained devices and is optimized for low-power, lossy networks. HTTP/HTTPS are standard web protocols that connect IoT devices to cloud-based services. AMQP is a secure and reliable open-standard messaging protocol used for routing and queuing data. DDS is a high-performance, real-time data distribution protocol, often used in demanding applications such as autonomous vehicles.

2.1.2 Role of IoT in Creating Connected Systems

The Internet of Things (IoT) plays a crucial role in building connected systems by enabling seamless communication and data exchange between physical devices, software applications, and users. A key aspect of IoT is ensuring interoperability and integration across diverse hardware, software, and data sources. This requires scalable and secure infrastructure designed by network architects, while system analysts ensure compatibility through testing, configuration, and troubleshooting. IoT also drives data-driven decision-making by collecting real-time data through sensors, which analysts and scientists use to uncover patterns, predict trends, and generate actionable insights. In various industries, IoT is transforming operations through automation. For instance, in healthcare, wearables support remote monitoring and emergency response; in transportation, GPS and condition-monitoring sensors optimize fleet management and safety; and in finance, IoT-enabled POS systems enhance fraud detection and cybersecurity through real-time monitoring. Additionally, IoT enhances user experience by providing intuitive dashboards designed by UI/UX professionals, ensuring that even non-technical users can interact effectively with IoT systems. Cybersecurity is also strengthened through real-time monitoring of connected devices, with automation and security software helping to detect and mitigate threats such as fraud or unauthorized access. Lastly, IoT supports scalable infrastructure, where software developers build robust applications that enable automation, AI integration, and continuous system updates to manage data efficiently and reliably.

2.1.3 Rise in IoT Technologies

Significant growth has been observed in the landscape of the Internet of Things in recent years, with projections indicating continuous expansion in the coming decades. This section presents an overview of the IoT market's progression from 2022 to 2023, along with forecasts extending to 2033. Fig. 1 presents the market trends of the Internet of Things (IoT) in terms of percentage growth over different time periods. It shows a gradual increase from around 15% in 2022 to approximately 20% during 2022–2024, followed by a significant rise to nearly 50% in the 2024–2033 period. This indicates an accelerating growth pattern, highlighting the increasing adoption and expansion of IoT technologies in the coming years.

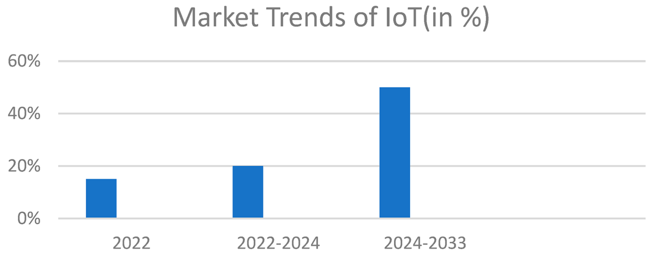

Figure 1: Market trend of IoT.

Between 2022 and 2023, the number of active IoT devices globally reached approximately 16.1 billion by the end of 2023. Looking ahead, the number of IoT devices is expected to grow significantly, reaching around 39.9 billion by 2033, representing a compound annual growth rate (CAGR) of 10% over the decade. Among the key drivers of this growth are Low Power Wide Area (LPWA) technologies, such as LoRaWAN, which are projected to see a substantial increase in connections from around 360 million in 2023 to over 2 billion by 2033.

2.2 Robotics

Robotics is a multidisciplinary field that merges various engineering disciplines, including Computer Science, Electrical Engineering, Mechanical Engineering, and Artificial Intelligence (AI), to design, construct, operate, and apply robots in a variety of fields to improve work efficiency, reduce the lack of manpower, and obtain the utmost benefits from this technology. Robots are computerized machines programmed to simulate humans, interact, and perform complex tasks. Developments in this field have led to the creation of robots made from flexible and deformable materials. The design includes structural aspects, adaptability to complex and unstructured environments, the increasing use of robotics in the medical industry, and exploration of designs that mimic human movement.

To operate effectively, robots need to perceive their environment, which requires advanced sensors such as ultrasonic sensors, sound sensors, infrared line-tracking sensors, and many more. Mapping algorithms for simultaneous localization are developed to define pathways for robots [5]. 'Unimate,' the first industrial robot, was introduced in 1960 to automate manufacturing tasks such as welding and metalworking in car factories.

Since then, robotics has evolved significantly, incorporating artificial intelligence, machine learning, and the Internet of Things to enhance its functionality and intelligence [6]. Table 2, consisting of components of Robotics along with their functions and appropriate examples.

Table 2: Components of robotics.

Sno	Components	Functions	Examples
1	Power Supply	Provides the energy to the robot depending on its design and function.	Batteries, solar power, or wired electrical sources.
2	Actuators	Converts energy into movement, which allows the robot to move its parts and perform tasks.	Motors, Hydraulic systems, and Pneumatic systems.
3	Sensors	Enable the robots to perceive their environment, helping robots to make informed decisions.	Ultrasonic sensor, sound sensor, temperature sensor, etc.
4	Controllers	Acts as the brain of robots, processes information from sensors, and issues commands to actuators.	Arduino Uno.
5	End Effectors	These devices are connected to the end of a robotic arm or leg to associate with the surroundings.	Some examples are welding torches & surgical instruments.
6	Driver	Determines how the robot moves.	Wheels, tracks, or legs.
7	Software	Providing prog. and logic for robot operations.	Arduino IDE

2.2.1 Types of Robots

- Industrial Robots: Such robots are the workhorses of production industries, which reduces the lack of manpower in industries and are used for tasks like welding, assembling, and material handling; often fixed in place and best known for the precision in work.
- Collaborative Robots: Designed to assist and work alongside humans in shared workspaces; used for tasks that require the blend of human skills and robotic precision.
- Autonomous Mobile Robots: These are designed to navigate independently in the environment with the use of sensors and AI to map their pathway and avoid obstacles.
- Humanoid Robots: Designed with features that resemble humans and function; used in the task which need human agility, like research, entertainment, etc. The usage of such robots extends to assist in elder care or work in environments lethal to humans.
- Service Robots: These robots are designed to help humans in everyday settings, which include the cleaning robots, Hospitality robots, and delivery robots.
- Medical Robots: These robots minimize the invasiveness and provide increased precision during surgeries, and they are also used for rehabilitation and drug delivery.
- Aerospace Robots: Such robots are designed and used in space exploration and within the aerospace industry.

2.2.2 Autonomy and Control Systems in Robotics

Autonomy and control systems are crucial aspects of robotics, determining how independently a robot can perform tasks, how it processes and executes commands. It depicts the ability to perform tasks with human interference. The level of autonomy can range from fully manual to completely autonomous systems:

- Tele-operated Robots: Controlled remotely by humans, often used in hazardous environments.
- Semi-Autonomous Robots: Designed to perform definite tasks freely, yet need some human control or input for complicated decisions.
- Fully Autonomous Robots: Capable of operating without any human assistance, using sensors, AI, and machine learning algorithms to adapt to their environment.
- Collaborative Robots: Work alongside humans, adjusting their actions based on human movements and commands, commonly used in manufacturing and healthcare.

Control systems govern how robots interpret instructions and perform tasks. They ensure the robot's movements and actions are accurate, safe, and efficient. Key types of control systems include:

- Open-loop control systems: Execute predefined tasks without feedback from the environment. These systems are simpler but lack adaptability.
- Closed-loop control systems: Take the feedback from sensors to alter operations in real-time, enabling adaptability and precision.
- Supervisory Control: A human operator oversees a group of robots, providing high-level guidance while the robots execute detailed actions autonomously.
- Adaptive control systems: Modify their operations based on environmental changes and learning from experience, commonly used in AI-powered robots.
- Swarm Control system: Enable multiple robots to work together by communicating and coordinating their actions, inspired by the behavior of social insects like ants and bees.

2.2.3 Rise in Robotics

Fig. 2 illustrates the projected growth trend of the robotics industry up to 2033, highlighting a steady and continuous increase in market expansion over time. The graphical representation indicates that the industry experiences gradual growth in its early stages, followed by a more pronounced upward trajectory in the later years, ultimately reaching an estimated growth rate of around 18% by 2033. This consistent rise reflects the increasing adoption of robotics across various sectors, driven by advancements in artificial intelligence, machine learning, and automation technologies.

Additionally, the expanding shaded region in the graph signifies a corresponding increase in market size and investment, emphasizing the growing economic significance of robotics. Despite minor inconsistencies in year labeling, the overall trend clearly demonstrates that the robotics industry is transitioning into a phase of accelerated development and is expected to play a pivotal role in shaping future technological innovations and industrial automation.

The global robotics market was valued at approximately USD 46 billion in 2023 and is estimated to reach around USD 47.9 billion in 2024, reflecting steady growth. Looking ahead, the market is projected to surpass USD 211.1 billion by 2034. This significant expansion is expected to be driven by continuous innovations in artificial intelligence (AI) and machine learning (ML), as well as the increasing adoption of robotics across diverse sectors such as manufacturing, healthcare, logistics, and agriculture.

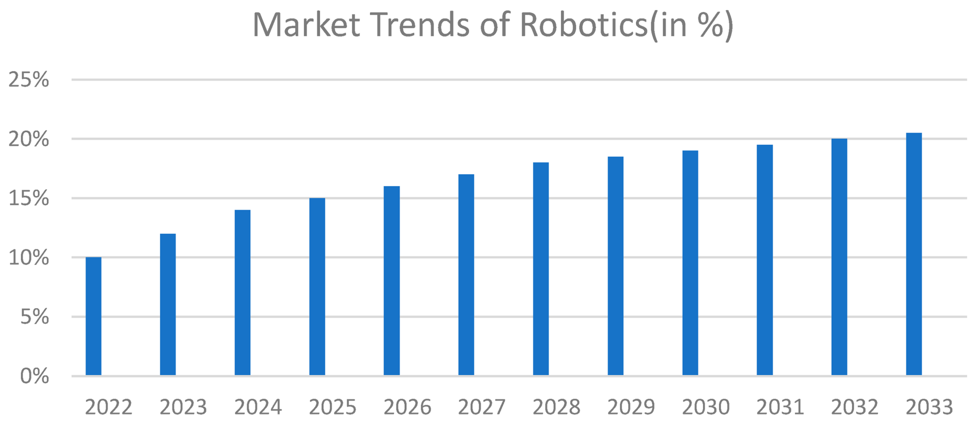

Figure 2: Market trend of robotics.

2.3 Convergence of IoT and Robotics

The Internet of Robotic Things (IoRT) combines technologies like AI, machine learning, IoT, robotics, and cloud computing to enable intelligent sensing, tracking, and interaction. It features self-adapting networks and edge nodes that connect local and external systems. Robots use Network Interface Cards (NICs) for communication, and data is transferred using protocols like TCP/IP. IoRT also employs Digital Twin Technology to create real-time virtual replicas of physical systems. An example is Sophia, an advanced humanoid robot that uses AI and neural networks to understand gestures, emotions, and interact like humans [7].

Leaking of data while exchanging data is a huge issue; the security importance in IoRT is crucial, as often the robots have a wireless connection with a file server. A subnet and router's static IP address is created by the network associations, which is globally exposed; it is the main cause of data attacks in robots. Robots contain a static IP address and Distributed Ledger Technologies (DLTs), which provide systematic data management and are linked with IoRT frameworks concerning security, privacy, and safety [7].

As shown in Table 3, IoRT combines primary abilities such as perception, motion, and sensing with secondary abilities like decision-making, interaction, and cognition, along with architectural features including configuration, adaptability, and dependability.

Table 3: Abilities of IoRT.

Primary-Level Abilities	Secondary-Level Abilities	Architectural-Level Abilities
Perception	Decision	Configuration
Motion	Interaction	Adaptability
Sensing	Cognition	Dependability

2.4 Emerging Technologies in IoT & Robotics

The integration of IoT and robotics has led to advanced innovations, allowing robots to process and share real-time data efficiently. Edge computing enhances performance by reducing latency, while technologies like SLAM, wall following, and sensor fusion improve environmental mapping and navigation. Algorithms such as AEKF, BFS, and DFS enable accurate path finding and error correction. Mobile surveillance robots use PID control for movement and media capture, and secure communication is maintained using the MQTT protocol.

Various techniques and algorithms enhance autonomous robot navigation and performance. The PID (Proportional-Integral-Derivative) controller helps maintain a safe distance from walls and ensures a quick response to sudden path changes. Wall following allows robots to navigate indoor environments by tracking walls and avoiding obstacles, using ultrasonic sensors to measure distance and adjust movement. Controllers for this process may use Kalman Filters (KF, EKF), fuzzy logic, or neuro-fuzzy systems. The SLAM (Simultaneous Localization and Mapping) technique helps accurately detect walls and doors as obstacles, with improved precision through KF and EKF. Depth-First Search (DFS) and Breadth-First Search (BFS) algorithms assist robots in navigating by finding reachable paths and optimal routes. BFS uses matrix representation to define start and end nodes, while DFS explores paths deeply until a goal is found or no further traversal is possible [8].

3 Literature Review

The IoT and evolution of robotics have gained spotlight in the past decades. It is acknowledged by the industries, the academy and society that even the government institution, several alliances and enterprises have been conscious of its importance and highlighted the potential benefits attained from IoT. This leads to the launch of strategic projects and initiatives aimed at developing IoT profitably [9]. In the past few years, the logistics industry has also taken advantage of IoT technologies, which have had a considerable impact. IoT provides visibility and traceability, which have had a positive impact on safety and control in the logistics industry [10]. IoT is considered a game-changing technology, with the expansion of its applications across a vast variety of real-time scenarios and domains [11]. The necessary information provided by IoT supports context-aware services, which work in the background of smart space development. The rapid surge of numerous technologies has endorsed the concept of IoT in aspects such as radio-frequency identification (RFID), mobile communication, lightweight protocols, and wireless sensor networks. The foundation of IoT pivots on the high-powered interconnection of multiple physical units in a wired or wireless paradigm to assist intelligent sensors, actuators, and other necessary components.

Mark Weiser, in the early 1990s, suggested the concept of ubiquitous computing, later considered to be pervasive, where it relies on ubiquitous networks and scaling to hundreds of computers per room, along with advancements in embedded computing technologies. Perhaps Weiser faced the main challenge of designing its operating system in such a manner that it could allow software to fully exploit network capabilities. The development of sensor nodes began in the mid-1990s, with multiple technologies such as wireless communication and digital electronics representing important advancements. The term 'embedded computer system' was used in 1974 to describe a computer that is physically included within a larger system, which does not primarily process data but supports integration, design, acquisition, and operational aspects. Implementation is carried out using microcontrollers and single-board computers (SBCs) [9].

Industry leaders and specialists were invited to come together and showcase the significance of IoT at the IoT World Congress held in June 2015 and again in 2016 in Barcelona, Spain. Reforming logistics with the help of IoT has given rise to projects in areas such as warehousing, vehicle tracking, communication between vehicles, routing, product quality management, supply chain management, and certification [10]. IoT technologies foresee their evolution in the form of smart city programs becoming a reality. The objective is to establish a robust ecosystem with increased efficiency and optimized city operations, thereby creating new opportunities that improve the lifestyle of citizens. Infrastructure deployment for traffic, water, parking, energy, public transportation, waste management, public safety, street lighting, and many other areas enables sensing of important data and parameters within the city, as well as control and responsive actions [11].

The evolution of IoT has integrated smart services into our daily lives. Specially-abled children use autism glasses to interact, while people with disabilities manage tasks with the help of IoT-assisted devices.

Health-tracking wearables have made self-monitoring easier, helping patients maintain balanced diets. Considering an example of IoT-enabled route tracking, Google Maps and other navigation tools provide real-time information about traffic congestion and suggest alternate, optimized routes to reach destinations faster. Similarly, in the agriculture field, smart services can predict crop yield, determine suitable fertilizers, and identify disease-prone crops along with preventive measures [11]. IoT can transform energy usage in power systems, enabling smarter operations and efficient microgrids through better integration and coordination of electrical devices [12].

Similar to the Internet of Robotic Things, there is another subfield of IoT, i.e., the Internet of Medical Things (IoMT), in the healthcare sector. Innovations such as the AliveCor Heart Monitor record, store, and transfer ECG rhythms of patients and provide insights into heart activity and potential causes of heart-related issues. The sensors used in these devices play a critical role and act as a bridge between the physical world and information systems by gathering various types of data. Sensors used in medical devices measure temperature, blood pressure, heart rate, weight, and glucose levels, and are connected through wireless sensor networks to transfer useful information to patients, medical staff, and doctors [13].

From 1990 to 2025, the transformation of IoT has created a significant impact on technology. Earlier limitations, such as the lack of suitable operating systems and wireless communication for IoT devices, have been overcome, transforming the entire concept of IoT. Hence, it is anticipated that further research will continue to enhance this technology in the near future. In industry, robots use machine learning (ML) algorithms to learn, respond adaptively, and simulate responsive behaviors [14]. The implementation of mobile robots in various fields such as defense, security, medical treatment, disaster-prone areas, hospitality, and others has helped reduce the need for manpower, as robots are efficient and faster than humans.

Robots are multifunctional and reprogrammable, designed to move materials and tools with the help of motion sensors and variable programming to perform multiple tasks. These autonomous robots follow three steps to perform a task: perception, planning, and movement [15]. Robotics is inspired by the 'Darwinian Theory of Evolution', which explains how species change over time through natural selection. Small inherited variations help organisms survive and reproduce in their environment. Similarly, evolution in robots, even with small variations, helps them survive in unpredictable environments, and these variations over time contribute to the advancement of the robotics field.

Modular robots are a type of robot developed using multiple units or modules, such as sensors, actuators, microcontrollers, and shaft motors, providing versatility, as the robot can be configured in different ways. This self-reconfiguration allows the robotic system to perform numerous tasks in different environments. If any module fails, another module can replace it, increasing the robustness of modular robots [14]. This part of the research paper presents the timeline of robotic development and evolution to understand how technology has progressed from its initial stages to the advanced state of robotics today.

Table 4 gives the year wise evolution of Robotics along with the details of Inventor and a brief discussion.

Table 4: Evolution of robotics.

Year	Robot/Inventor	Description
1950	Robot George	Tony Sale from the United Kingdom built the first humanoid robot of 182.88 cm tall with the ability to talk and walk [15].

(Continued)

Table 4 (continued)

Year	Robot/Inventor	Description
Late 1960	Robot Shakey	Wrote the history of mobile robots; it has the capabilities of understanding and causing the occurrence in the surroundings. Under the supervision of Charles Rosen an engineer's group from Stanford Research Institute (SRI) developed Robot Shakey and worked with the funds of Defense Advanced Research Project Agency (DARPA) [15].
1970	Kirk et al.	Proposed a dual-mode algorithm and gaussian function to send an intelligent mobile Rover to other planets to explore the uncertain terrain and to find the optimized path for the rover, respectively [15].
1975	Cahn et al.	Proposed an algorithm to find the solution to the robot navigation problem and avoid obstacles using the formation of a range limited environment [15].
1979	McGhee et al.	Used heuristic algorithm to avoid the terrain that constitutes a region not fit for weight bearing [15].
1981	Blidberg	Researched about the types of microprocessors and their impact on the intelligent robot in case of extending the size of memory, processing distribution, does it affect the capabilities of mission, communication control, and navigation [15].
1983	Robotics Institute of Carnegie Mellon	Developed CMU rover and Thorpe researched on the navigation, and working principle of the CMU rover [15].
1985	Keirseg et al.	Worked on the development of technology of the intelligent vehicle control. The main focus was to implement to technology of Artificial intelligent in autonomous system [15].
1987	Harmon et al.	Invented a field surveillance robot which move independently in the unfamiliar environment. It has vision-ranging sensors to avoid the obstacles [15].
1988	Borenstein et al.	Used ultrasonic sensor to avoid the obstacles and explained the limitation on the algorithm of obstacle avoidance [15].
1989	Luo et al.	Proposed the method to integrate multiple sensors technology to an intelligent robot to enhance its functional capabilities [15].
1990	Griswold et al.	Gave an optimal control approach applied on mobile robots to avoid collision with the moving objects [15].

(Continued)

Table 4 (continued)

Year	Robot/Inventor	Description
1991	Shiller et al.	Presented the method which control speed and computative path that reduces the motion with time considering surface mobility, vehicle dynamics, obstacle and terrain topography [15].
1992	Manigel et al.	Present a method by which mobile robots are controlled by computer vision. The algorithm used are geometric coordinates and Kalman filter to trace robot's position on the roadways [15].
1993	Yuh et al.	Proposed the Neural Network controller by which robots can be controlled remotely [15].
1995	Chen & Burdick	They used genetic algorithm which optimizes the distinct nature of the domain based on assembly matrix which represents the configuration of robotic model [14].
1997	Hall et al.	Gave research on multiple sensory data fusion to explain how the robot process models, data fusion and identification technique uses [15].
2000	Robot Polybot	This modular robot has feature of self-reconfiguration that was implemented to explore the real-time possibilities of making robots using many modules; Also, capable to change its configuration and mobility depending on the environment in which it is deployed—Rolling over terrain, climbing on hilly terrain and an earthworm to move around obstacles [14].
2002	Robot Telecubes	Was introduced by Suh et al. and it is a compact cubic module of 4 side which is capable of self-reconfiguration due to this it can expand itself more than twice of its length [14].
2004	Robot ATRON	It is an open framework system which consist roughly ball-shaped modules and it is self-reconfigurable robot; Uses the Artificial neural network to control it [14].
2007	Robot Molecubes	For modular robotics it provides platform with the integration of software and hardware, helps to develop to eliminate the hurdles to accelerate progress—To evolve the modular Neural network control of robot simulation it uses the genetic algorithm [14].
2011	Robot U-Bot	It is composite system combining the lattice and chain self-reconfigurable robots and capable of multimode locomotion [14].

(Continued)

Table 4 (continued)

Year	Robot/Inventor	Description
2012	Robot SMORES	Self-Assembling Modular Robot for Extreme Shape-Shifting (SMORES)—Was designed to enhance the self-reconfigurable robots to allow the robots to configure using lattice, chain and mobile classes [14].
2014	Endres et al.	Suggested the new mapping system using a Red Green Blue—Depth camera to create a 3D map with higher accuracy [15].
2015	Dong et al.	Look over the issue of design and development of control probe for UAV (Unmanned aerial vehicles) Swarm robots to get pre-established time dependent formations [15].
2019	Nicholson et al.	Gave the technology for 2D object detection and evaluate a quadric 3 D surface for each object and position of camera [15].
2020	Yurtsever et al.	Talked about apparent technologies and usual practices in independent driving [15].
2021	Zhu et al.	Reviewed Deep Reinforcement learning algorithm and navigation framework on the basis of DRL algorithm conducted indoor & social navigation analysis, avoiding obstacle [15].
2022	Tesla Optimus Prototype	They presented the first working prototype of its humanoid robot—capable of picking up objects, walking and performing simple tasks [16].
2024	Tesla Optimus Gen2	It is the updated version of Tesla's Humanoid robot with faster, acrobatic and lightweight feature. It showcases the advanced movement, handling, and real-world application [17].

An investigation was conducted on the rover mobility system to determine the capabilities, design, and developing technologies required for a robotic rover to move in unknown planetary terrain. The mobility system of a rover indeed requires a large database for the automatic calculation of system performance under investigation [18]. For planetary missions, some form of mobility is required for deployment. Considering the Martian surface, it is a challenging terrain with cluttered, varying-sized rocks that can act as obstacles for efficient rover mobility to achieve autonomous navigation. These rovers are designed with the capability to traverse long distances on planetary surfaces with minimal human intervention [19].

The realities of planetary exploration began in 1957 with Sputnik, heralded as the first spacecraft, with the goal of exploring beyond Earth's orbit. The next attempt, the United States' Pioneer 0 (lunar orbit), was ultimately unsuccessful. Later, in 1960, during the first Mars mission, the Soviet Union launched Marsnik-1, which also failed. The United States and Russia, through continuous efforts, made twenty-one and nineteen Mars exploration attempts, respectively [20]. In December 1996, the Pathfinder mission to Mars was launched by NASA with the objective of studying Martian rocks. The rover was well equipped to perform a high level of autonomous goal-seeking and obstacle-avoidance behavior due to round-trip delay time [21]. Sojourner was another robotic rover, a part of NASA's Pathfinder mission, which landed on Mars in 1997 [22].

Luna 21 landed on the Moon in 1973 and traveled about 37.7 km, but the mission failed because loose soil became stuck in the rover's wheels, causing slip-sinkage. It is crucial for rover wheels to travel on sandy terrain without sinking into the soil or getting stuck in obstacles [23]. ExoMars (2009)—This mission's core goal was to determine whether life exists on Mars. It is a collaborative program of the European Space Agency (ESA) and Russia's Roscosmos. The Rosalind Franklin rover was designed to drill deep into the Martian surface to investigate evidence of past life. It was scheduled to launch in 2022 but was postponed after Russia's attack on Ukraine. It is now rescheduled to be launched in 2028 [24].

NASA's Perseverance rover was launched in 2020 and landed on Mars in February 2021. It is a nuclear-powered rover and has identified evidence of an ancient lake, 'Wildcat Ridge,' along with discoveries related to the planet's volcanic history, surface, and interior [25]. The Zhurong rover from China landed on Mars in May 2021 and provided information about the geology of the Utopia Planitia region.

4 General Methodology of IoRT

To understand the concept of Internet of Robotic Things, we must learn about its architecture which is divided into five layers i.e., Hardware layer, Network layer, Internet layer, Infrastructure layer and Application layer as shown in Fig. 3. Each layer hold significance in building IoRT to work efficiently.

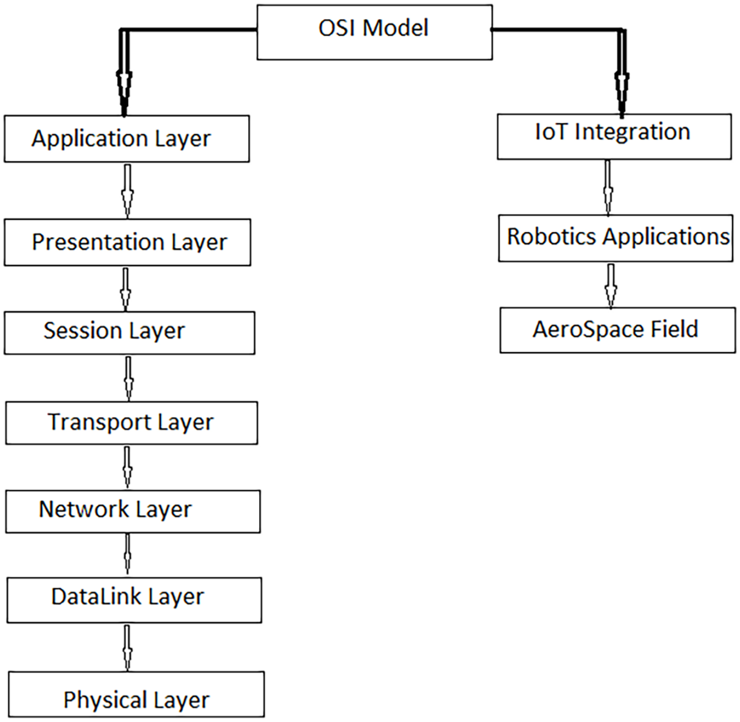

Figure 3: General methodology of IoRT.

Physical layer: Considering the OSI (Open system interconnection) model, this layer is the lowest layer consisting various physical things or robots like sensors, actuators, defense equipment, home appliances, mobile phone, etc. [26]. This layer concise all the gathered complex data and transfer it to the edge nodes which passes it further towards network and control layer [27].

Network layer: This layer provides several types of network connectivity options and it is the second most layer of the IoRT architecture which includes the cellular connections—3G & LTE/4G. It also offers few short-range communication technologies such as Bluetooth, 6LoWPAN, wi-fi, Broadband global area network etc., Providing the seamless communication between the nearby robotic Things [26]. The network layer is further divided into two sub-layers: Routing layer maintains the transmission of data packet from one-end robot to the destination robot. Encapsulation layer encapsulates the data packets to hide necessary information. Routing protocol for low power and lossy network (RPL), IPv6 over low power wireless personal area network (6LoWPAN), Cognition RPL, channel-aware routing protocol (CARP) are used as routing protocols for Internet of Things and Internet of Robotic Things [27].

Internet layer: The internet connectivity paves the way of whole communication of IoRT architecture. For the efficiency the IoT has specific communication protocol and added in this layer. UDP, IPv6, MQTT (Message queuing telemetry transport), DTLs (Distributed ledger technologies), etc. used for the following tasks: multicast support, Real-time messaging, spreading of network embedded system, an alternate for TCP, queuing message for middleware environment, providing privacy to UDP and many more.

Infrastructure layer: For the advanced robots the M2M2A (Machine to Machine to Actuator) is suitable and shall contribute to the IoRT system. The M2M2A consist various sensors and robotic technologies which holds practical solution to the real-life problems. In such scenario the sensors inter-linked among them and hatch the anticipated actions and reflexes made to be performed by the robots.

Application layer: It is the topmost layer in IoRT architecture with its function relying on the programs which implemented fully to process, observe, control and organize with mobile robots and environment parameters.

5 Comparative Analysis

The comparative analysis section provides a detailed description of multiple Mars missions based on their objectives, technologies, approximate costs of exploration, and mission outcomes. The analysis helps us understand how technologies such as network systems, multiple sensors, and other celestial instruments assist planetary missions in gaining insights into the planet's atmosphere and surface.

The comparison given in Table 5 provides insights and analysis of the Mars missions. These missions are not restricted only to observing the surface and atmosphere of the Martian environment but have also led to discoveries of the Martian moons, Phobos and Deimos, the solar system's largest volcanoes, layers of regolith on the Martian moon's surface, Valles Marineris, polar caps, and a point source recorded as Deimos with respect to the bright star Aldebaran and the planet Jupiter. This creates a sense of wonder about Mars, and it can be assumed that there is much more to learn, with the expectation of further discoveries in the near future.

Table 5: Comparison based on objective.

Spacecraft	Organization	Objectives/Discoveries
Mariner-4 (Flyby)	NASA	Launched in 1965, were focused on Mars surface, analysis of composition and structure of Martian atmosphere and capture close-up images of planet [28].

(Continued)

Table 5 (continued)

Spacecraft	Organization	Objectives/Discoveries
Mariner-6 & 7 (Flyby)	NASA	Launched in 1969, First dual mission Mars flying over equator & south poles region, analysis of atmosphere and surface of Mars, using remote sensors and recording 100's of picture [28].
Mariner-9 (Flyby)	NASA	Launched in 1971, First spacecraft to enter another planet's orbit. Aim was to investigate the Mars surface and atmosphere but were fortunate to discover the Martian Moons (Phobos & Deimos) during close flyby. It also discovered the Solar System's largest Volcanoes, Marineris valley, Olympus Mons, huge canyon system and polar caps [28].
Viking Orbiter/Lander	NASA	Launched in 1976, this project placed two Spacecrafts in the orbit of Mars and 2 Lander on the Surface of Mars. It discovered that the superficial layer of Phobos and Deimos covered with sheer Regolith and Phobos has a rotational liberation force of about 1° magnitude [28].
Phobos-88 (Phobos-1 & 2)	Soviet Space Probe	Launched in 1988, two Spacecrafts went to Mars for 3 months and landing on Phobos came within the range of 100 km– Also took many orbiters & landers apparatuses to observe the Martian environment and surface of Phobos [28].
Mars Pathfinder	NASA	Launched in 1996, Pathfinder Rover used Mars Pathfinder (IMP) camera for multispectral measurement of both Phobos and Deimos [28].
Mars Global Surveyor (MSG)	NASA	In 1997 entered in the orbit of Mars & worked seamlessly for upto10 years. It was flying approx. 400 km high on Mars so had no chance to near flyby [28].
Mars Odyssey	NASA	In October 2001 spacecraft unknowingly went into the lower orbit—failed to observed the Phobos and Deimos. Perhaps on February 2012—The shadow of Phobos was observed by Thermal Emission imaging system camera (THEMIS) and it's still operating [28].
Mars Reconnaissance Orbiter (MRO)	NASA	In August 2006 orbiter entered into low, spherical orbit. Took about 500 images of Deimos star 100 Phobos star image. Till now it is working and expecting to append intermittently new observations of Phobos and Deimos [28].

(Continued)

Table 5 (continued)

Spacecraft	Organization	Objectives/Discoveries
Mars Exploration Rover (MER)	NASA	Launched in 2003 and landed on Mars in 2004—It has three major objectives: (a) To probe the Mars surface with the greater probability of consisting proofs of liquid water. (b) To diversify the rocks and soil by their characteristics to witness past activity of water. (c) To extract evidence for environmental conditions when water was present to assess whether life is possible or not [29]. Across the sun 2 Mars Exploration rovers took multiple images of Phobos and Deimos transiting.
Mars express mission (MEX)	European Space Agency (ESA)	Landed on 25 December 2003 on Mars; The lander Beagle 2 part of the mission off the right track after entering in the atmosphere. The aim of the Mars express mission orbiter was to successfully positioned in elliptical-shaped orbit of Mars of a gradient of 86.6° [28].
Rosetta	ESA	Launched in March 2004, but landed on a comet in August 2014. Spacecraft flew by the gravity of Mars to assist before proceeding its journey towards the comet [28].
Curiosity	NASA	Observing Phobos/Deimos solar transits, mutually run into and encounter with Saturn and Jupiter to support evolution of orbit and interior studies of Mars [28].
Nozomi	JAXA	Its primary goal was to study Mars upper atmosphere and to associate with solar flares coming from sun perhaps the mission was unsuccessful due to the faulty valve meantime of earth flybys led to the loss of Propellant [30].
Mangalyan	ISRO	First mission of India to Mars—launched in November 2013. The aim is to test interplanetary exploration technologies and to study the Martian surface and atmosphere & to demonstrate India's capabilities to reach on Mars Orbit [31].

Technological comparison of the Mars Missions comprehends the advancement of the spacecraft with the exploratory technology including Infrared and Ultraviolet instruments sensors, High resolution imaging system, Radar system, Aeroshell and many more science experiments. Table 6 gives a comparison based on technologies involved, approximate cost and mission outcome.

All these advanced technologies helped in observing the surface of Mars and its environment. Phobos-1 was partial successful, When the Spacecraft was launched it was operated according to the plan and completed its 'First Phase' journey successfully. Perhaps on 02 September 1988 it lost the communication from Earth permanently due to human error which caused the uploading of wrong command by the ground controller which led to the shutting down of Spacecraft. The Nozomi Mission was failed due to the faulty valve caused loss of the propellant and the solar winds caused damage to the Spacecraft's power and heating system.

Table 6: Comparison based on technologies, cost and outcome.

Spacecraft	Technologies Involved	Approx. Cost ($)	Mission Outcome
Mariner-4 (Flyby)	Used Vidicon camera. Instrument to measure cosmic dust, cosmic rays, magnetic field and solar plasma [32].	83.2 million	Successful
Mariner-6 & 7 (Flyby)	Carried Mars wide and narrow angle TV camera, Infrared spectrometer, 2-channel IR radiometer, Ultraviolet spectrometer, Thermal control flux monitor and celestial mechanics' experiment [28].	148 million	Successful
Mariner-9 (Flyby)	Wide angle camera—11° × 14° field view, Narrow angle camera—1.1° × 1.4° field view. 7329 images were taken. IR radiometer, UV spectrometer, IR interferometer, spectrometer, TV system and celestial mechanics occultation experiment [28].	129 million	Successful
Viking Orbiter/Lander	Both orbiters—had Imaging system, IR thermal mappers, detectors to detect the water in Mars atmosphere and radio science experiment to observe Phobos and Deimos during close flyby [28].	1 billion	Successful
Phobos-88 (Phobos-1 & 2)	Carried instruments to analyze the Martian environment and surface of Phobos, Imaging systems, Spectrometers to analyze the chemical composition of Phobos's surface, Laser for vaporizing small spots on Phobos, radar for probing subsurface of Phobos and hopper lander to move across surface of Phobos [28].	163 million	Phobos-1: Partial Successful Phobos-2: Successful
Mars Pathfinder	Atmospheric structure instrument/Meteorology package (ASI/MET) for atmospheric pressure, wind & temperature giving important meteorological data, Alpha Proton X-ray spectrometer (APXS) Sojourner—carried it to analyze elemental composition of rock and soil and Airbag landing system helps the spacecraft bounced multiple times before coming to stop [33].	265 million	Successful
Mars Global Surveyor (MSG)	Remote sensors—Thermal Emission spectrometer (TES), Mars orbiter later Altimeter (MOLA) and Mars orbiter camera (MOC) [28].	225 million	Successful

(Continued)

Table 6 (continued)

Spacecraft	Technologies Involved	Approx. Cost ($)	Mission Outcome
Mars Odyssey	Mars Radiation environment experiment (MARIE), Gamma Rays Spectrometer (GRS), Hzdrazine propellant, Thermal Emission imaging system (THEMIS) and Mapping technology [34].	297 million	Successful
Mars Reconnaissance Orbiter (MRO)	Context Camera (CTX), High Resolution Imaging Science experiment (HiRISE), Compact Reconnaissance Imaging spectrometer for Mars (CRISM) Mars color Imager (MARCI), SHARAD (Shallow subsurface sounding radar)—searches for underground water on Martian surface and Mars orbiter later Altimeter (MOLA) [35].	716.6 million	Successful
Mars Exploration Rover (MER)	Artificial Intelligence—Adaptive Sampling (PIXL instrument), Sensors (MEDLI2 & MEDA), Supercam (Camera, laser and spectrometer), Software—Rover flight software (FSW) and Vx works Operation system & Aeroshell [36].	1.08 billion	Successful
Mars express mission (MEX)	UV & IR atmospheric spectrometer (SPICAM), Visual Monitoring camera (VMC), High Resolution Stereo camera (HRSC), Visual IR Mineralogical mapping spectrometer (OMEGA), Mars advanced Radar for subsurface & Ionospheric sounding (MARSIS), Planetary Fourier Spectrometer (PFS) [37].	150 million	Successful
Rosetta	UV spectrometer called Alice and Ion & Electron sensor (IES), Microwave instrument for Rosetta orbiter (MIRO)—These includes 11 science instruments boarded for the mission [38].	1.8 billion	Successful
Curiosity	Mars Descent Imager (MARDI), Mastcam, Mars Hand Lens imagers (MAHLI), Navigation cameras (Navcams), APXS, Chemistry and camera (Checam), Hazard-avoidance camera (Hazcams), Sample analysis at Mars (SAM), chemistry and mineralogy X-ray diffraction (ChenMin), Radiation Assessment detector (RAD) & Dynamic Albedo of Neutrons (DAN) [39].	2.6 billion	Successful

(Continued)

Table 6 (continued)

Spacecraft	Technologies Involved	Approx. Cost ($)	Mission Outcome
Nozomi	Carried 14 instruments—cameras for imaging, mass neutral spectrometer, dust counter, thermal plasma analyzer, magnetometer, electron and ion spectrum analyzers, Ion mass spectrograph, High energy particles experiments, VUV imaging spectrometer, sound and plasma wave detection, LF wave analyzer, electron temperature probe and a UV scanner [40].	848 million	Unsuccessful
Mangalyaan	Thermal IR imaging spectrometer (TIS), Mars color camera (MCC), Lyman Alpha Photometer (LAP), Mars exospheric neutral composition analyzer (MENCA), PSLV C-25 rocket and liquid apogee motor [41].	71 million	Successful

6 Practical Implementation of IoRT in Space

Space exploration has also allured humans for decades. Advancements in technologies such as satellites, telecommunication, astronomy, and computing capabilities, along with the development of reusable rockets and spaceships, have made spacefaring more feasible and not limited to large national government initiatives. SpaceX's Crew Dragon, a spacecraft that was the first commercially built spacecraft, sowed the seeds of excitement among the community [42]. Startup companies in space technology have been manufacturing flexible space modules to operate in low Earth orbit, using it as a research space for exploration. These fascinating developments in the aerospace industry came to a peak on 18 February 2021, with the successful touchdown of the National Aeronautics and Space Administration's (NASA) Perseverance Mars rover, and on 14 May 2021, with the deployment of China's Zhurong rover on Mars [42].

The Mars Orbiter Mission (MOM) by the Indian Space Research Organisation (ISRO), also known as 'Mangalyaan,' was a successful mission that entered Mars orbit on 23 September 2014. It used an optimal energy transfer orbit to travel from Earth to Mars. It had a maneuvering system that included two star sensors, a solar panel sun sensor, four reaction wheels, and a main propulsion system. It carried a Methane Sensor for Mars (MSM) that measured the amount of methane present in the Martian atmosphere. In April 2022, Mangalyaan entered a long eclipse period that it was not designed to survive, and communication with Earth was irrecoverably lost [31].

The rise of Internet of Things (IoT) and robotics technologies and their deployment has become ubiquitous and easily attainable in terrestrial environments, with industries already using IoT-based networking for satellites to achieve wide-area connectivity. The Internet of Robotic Things (IoRT), particularly in space applications, represents a significant development for future generations, especially in mobile communication, where machine-to-machine communication for low-latency, mission-critical applications is expected to play an important role [42]. Mars rovers employ machine learning and AI algorithms to analyze terrain and make navigation decisions independently. By utilizing LiDAR sensors and high-resolution cameras, they detect and map the surrounding environment and calculate optimal paths, reducing dependence on Earth-based instructions [7]. Traditional space applications include the use of satellites to support telecommunication and the global positioning system (GPS), where low latency is essential for mission-critical operations. Hence, communication for rovers requires satellite networks, which are broadly classified based on their orbital distance from Earth [42].

Geosynchronous Earth orbit satellites are placed at an altitude of approximately 36,000 km above the Earth's surface. The orbital period of such satellites is about 23 h, 56 min, and 4.1 s. If a geosynchronous satellite is positioned directly above the equator, it is known as a geostationary Earth orbit (GEO) satellite. It remains visible at all times from a fixed location on Earth. GEO satellites are best suited for broadcasting and multipoint distribution applications. However, a major disadvantage for IoT applications is the propagation delay of about 125 ms. This delay can accumulate to around half a second, making it unsuitable for time-critical networks such as autonomous driving [42].

Non-geosynchronous orbit satellites are placed closer to Earth than geosynchronous satellites. Medium Earth orbit (MEO) and Low Earth orbit (LEO) are two well-known types. MEO satellites are placed at altitudes of 8000–20,000 km, whereas LEO satellites are placed at altitudes of 400–2000 km. The orbital period of MEO satellites is about 6 h, while that of LEO satellites is approximately 100 min or more [41]. Non-geosynchronous satellites are better suited for IoT applications, as their propagation delay is significantly lower than that of geosynchronous satellites [42].

The IoRT framework establishes communication between multiple robotic explorers. This collaborative approach increases mission efficiency, allowing one robotic entity to relay information to another, thereby forming a cooperative robotic ecosystem capable of extensive exploration. NASA's Mars rovers use the Deep Space Network (DSN), which acts as a cloud infrastructure, facilitating data transmission between Mars and Earth [42]. This network enables efficient storage, retrieval, and analysis of vast datasets collected by rovers, aiding researchers in gaining deeper insights into the Martian environment. IoRT systems are rapidly expanding across various domains, offering benefits but also introducing significant security challenges. Existing research mainly focuses on data confidentiality, system integrity, and AI- or cryptography-based defenses, while protocol-level security remains underexplored. This highlights the need for more systematic evaluation and robust, trustworthy security approaches for autonomous robotic systems [43]. This gap can be addressed by developing secure communication protocols with built-in authentication, encryption, and access control mechanisms, along with adopting standardized secure frameworks such as enhanced MQTT or CoAP. Additionally, systematic evaluation through simulation and real-world testing, combined with the integration of trustworthy and robust AI techniques, can improve the security and reliability of autonomous robotic systems.

7 Challenges and Limitations

This section presents a critical analysis of the key challenges and future prospects associated with the integration of IoT and robotics in aerospace applications. While the convergence of these technologies offers significant potential for automation and efficiency, several technical and operational barriers remain, including communication latency, data security, interoperability, and system scalability. This section highlights these limitations and discusses emerging trends and research directions aimed at overcoming them, thereby paving the way for more robust, intelligent, and reliable IoRT-based aerospace systems. Here are some of the identified challenges and limitations

- For vast distances establishing the real-time communication remain a challenging task, as it requires the enhancing of autonomous systems.
- Sometimes it also lacks in standardization which refers to the absence of standard communication protocols used for communication causing inefficiency and decreases its interoperability.

- Advancing the power supply technologies are indeed necessary to provide longer functional time and faster charging.
- If artificial intelligence is used the likelihood of algorithmic bias increases which can lead to unfair decision making by robots.
- It is quite challenging to set up necessary infrastructure for communication, data processing and power supply; maintaining and repairing of IoT-enabled robots can be expensive and complex too.
- Fabricating a safe interface and intuitive human robots' collaboration is a complex task.
- Enabling robots to implement algorithms in an unpredictable environment is a significant challenge.

The future of the Internet of Robotic Things holds enormous promise, anticipating the realization of flawless integration of these systems into our daily lives, enhancing efficiency and convenience across various sectors. It focuses on the advancement of autonomous robotic systems with the deployment of self-coordinating swarms for industrial and research applications. Human–robot collaboration will enhance AI-driven assistance, feedback, and interfaces. Research directions will focus on the advancement of sensor fusion and perception-enabled robots to map, perceive, and navigate through complex and unpredictable environments with the utmost efficiency and accuracy. Human 'digital twin' design will prioritize safety and social acceptability, whereas soft robotics and bio-inspired designs will explore applications in medical and fragile tasks. It will also play a significant role in developing advanced infrastructure such as automated traffic and security management, and environmental monitoring. A strong emphasis on energy-efficient and environmentally friendly robotic models will shape the future of sustainable robotic automation across industries.

8 Results & Discussions

This section presents a results-oriented analysis of the Internet of Robotic Things (IoRT), demonstrating that the convergence of IoT-enabled sensing, real-time communication, and autonomous robotics significantly enhances operational efficiency, system reliability, and adaptive intelligence, particularly within aerospace applications. The integration of IoT and robotics enables continuous data acquisition through sensor networks, which, when processed using edge and cloud computing, facilitates low-latency decision-making and improved system responsiveness. This leads to reduced human intervention, enhanced accuracy, and increased reliability in mission-critical operations conducted in dynamic and remote environments. Empirical findings further indicate that the incorporation of advanced techniques such as sensor fusion, machine learning, and distributed robotic architectures improves navigation precision, environmental perception, and task execution efficiency. Additionally, collaborative systems, including swarm-based robotic models, contribute to improved scalability, fault tolerance, and robustness. These performance-driven outcomes validate IoRT as a transformative paradigm capable of optimizing resource utilization while ensuring safety and precision in complex operational settings.

From an application-oriented perspective, the integration of IoT and robotics in aerospace systems provides measurable improvements in real-world scenarios such as satellite operations and planetary exploration. IoT-enabled sensors and communication frameworks support real-time monitoring, system diagnostics, and adaptive control in satellite systems, while in rover-based exploration, continuous environmental data facilitates obstacle detection, path planning, and autonomous navigation. The effectiveness of such integration can be systematically evaluated through simulation-based frameworks using performance metrics such as latency, response time, data accuracy, reliability, and degree of autonomy.

Furthermore, enabling technologies such as edge computing and sensor fusion play a critical role in supporting onboard decision-making and enhancing situational awareness. Communication protocols such as MQTT and CoAP ensure efficient and low-latency data exchange, thereby improving system scalability and responsiveness. The synergistic integration of artificial intelligence and machine learning with IoT further strengthens system intelligence by enabling predictive maintenance, adaptive control, and learning-based decision-making.

Collectively, these advancements establish a robust foundation for the development and validation of intelligent, autonomous, and data-driven aerospace systems, while also highlighting the need for continued emphasis on practical implementation and real-world validation.

9 Conclusion and Future Scope

The integration of the Internet of Things (IoT) with robotics, conceptualized as the Internet of Robotic Things (IoRT), represents a significant advancement in the evolution of intelligent and autonomous systems. This convergence has accelerated automation across diverse industrial sectors by enabling real-time data processing, autonomous decision-making, and efficient inter-robot communication. As a result, IoRT has emerged as a transformative paradigm with wide-ranging applications in smart infrastructure, industrial automation, and intelligent environments.

The future trajectory of IoRT indicates substantial potential for seamless integration into everyday life, enhancing operational efficiency, adaptability, and user-centric services. Developments in swarm robotics, human–robot collaboration, and AI-driven interfaces are expected to further expand its applicability in both industrial and research domains. Moreover, advancements in sensor fusion and perception technologies will enable robots to operate effectively in complex, dynamic, and uncertain environments with improved precision and reliability. Emerging areas such as human digital twins, soft robotics, and bio-inspired systems are likely to address critical challenges related to safety, adaptability, and interaction in sensitive and unstructured settings, particularly in healthcare and delicate task environments. In parallel, IoRT will play a crucial role in the development of advanced infrastructure systems, including intelligent traffic management, security frameworks, and environmental monitoring solutions.

Sustainability will remain a key focus, with increasing emphasis on energy-efficient and environmentally responsible robotic systems. Furthermore, the extension of IoRT into the aerospace domain highlights its potential to enhance spacecraft performance and support advanced space exploration missions. Considering the vast and largely unexplored nature of the cosmos, the development of such intelligent and autonomous technologies will be instrumental in enabling future exploration endeavors. In conclusion, IoRT stands as a promising and rapidly evolving field that is set to redefine automation, connectivity, and intelligent system design, thereby contributing significantly to the advancement of next-generation technological ecosystems.

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Ethics Approval: This article does not contain any studies involving human participants or animals performed by any of the authors. Therefore, ethical approval is not required.

Conflicts of Interest: The authors declare no conflicts of interest.

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