A Survey of Emerging Trends in Edge Computing

Research · May 2024

DOI: 10.13140/RG.2.2.22183.76962

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A Survey Paper

Distributed and Cloud Computing

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Date of Submission: 07-May-2024

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Abstract—**Edge computing has emerged as a pivotal paradigm in the realm of distributed computing, promising to revolutionize the way data is processed, analyzed, and utilized at the edge of the network. This survey paper provides a comprehensive overview of the current state of edge computing, encompassing its fundamental concepts, architectural models, enabling technologies, and diverse applications across various domains. We delve into the key characteristics of edge computing, including proximity to data sources, low latency, bandwidth optimization, and scalability, highlighting its potential to address the shortcomings of centralized cloud computing. Furthermore, we examine the multitude of technologies underpinning edge computing, such as edge devices, fog computing, edge analytic, and network slicing, elucidating their roles and functionalities within the edge ecosystem. Through an extensive review of existing literature and case studies, we identify and analyze the manifold applications of edge computing in domains such as the Internet of Things (IoT), smart cities, healthcare, autonomous vehicles, and industrial automation. Additionally, we discuss the significant challenges and open research issues surrounding edge computing, including resource management, security and privacy concerns, interoperability, and standardization efforts. By synthesizing and organizing the current body of knowledge on edge computing, this survey aims to provide researchers, practitioners, and policymakers with valuable insights into the advancements, opportunities, and unresolved issues in this rapidly evolving field.**

***Index Terms*—Edge Computing, Distributed Computing, Edge Devices, Mobile Edge Computing(MEC)**

I. INTRODUCTION

In today's digital world, our devices are more connected and data-driven than ever before. From smartphones to smart homes, the demand for instant access to information and services is driving the evolution of computing architectures. One of the most promising developments in this space is edge computing.

Edge computing is all about bringing computational power closer to where it's needed most—at the edge of the network, near the devices and sensors generating data. This shift away from traditional centralized cloud computing offers numerous benefits, including reduced latency, improved scalability, and enhanced privacy and security.

As we embark on this journey to explore the edge of innovation, it's essential to understand the various paradigms, technologies, and applications that define edge computing. This survey paper aims to provide a comprehensive overview of the state-of-the-art approaches in edge computing, highlighting emerging trends, challenges, and opportunities.

Throughout this paper, we will delve into the foundations of edge computing, examining its underlying principles and key architectural concepts. We will explore the diverse range of edge computing platforms and frameworks, from lightweight edge devices to powerful edge servers, and their roles in enabling distributed computing environments.

Moreover, we will discuss the myriad of real-world applications driving the adoption of edge computing across industries, including healthcare, transportation, manufacturing, and smart cities. By showcasing these use cases, we aim to demonstrate the trans-formative potential of edge computing in enhancing efficiency, enabling new services, and unlocking innovation at the edge.

In summary, this survey paper serves as a guide to navigating the rapidly evolving landscape of edge computing, providing insights into its current state, future directions, and the opportunities it presents for shaping the future of computing.

II. HISTORICAL CONTEXT

Edge computing has its roots in the evolution of computing architectures and networking technologies over the past few decades. In the early days of computing, large mainframe computers were the norm, and data processing was centralized in dedicated data centers. However, as computing technology advanced and the internet became widespread, the limitations of centralized processing became apparent.

The evolution of this computing paradigm has been carried through several stages since 1960. As shown in Fig. 1, each step influenced the concept directly or indirectly and changed the way EC is conceived.

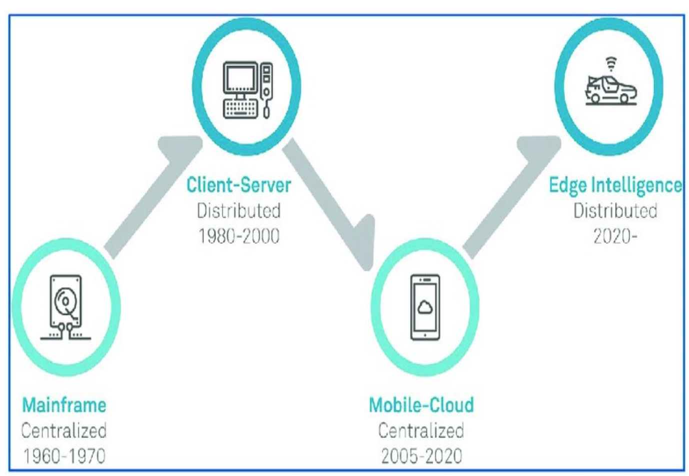

Fig. 1. Edge computing evolution chronograph.

The concept of edge computing began to take shape as researchers and engineers sought solutions to reduce latency and improve the performance of distributed systems. One of the earliest mentions of edge computing can be traced back to a paper titled "Active Messages: a Mechanism for Integrated Communication and Computation" by Thorsten von Eicken, David E. Culler, Seth Copen Goldstein, and Klaus Erik Schauser, published in 1992 [1]. This paper introduced the idea of moving computation closer to the data source to minimize communication overheads and latency in distributed systems.

Over the years, advancements in networking technologies, the proliferation of connected devices, and the emergence of cloud computing further fueled the development of edge computing. The increasing demand for real-time data processing and low-latency applications, such as IoT devices, autonomous vehicles, and augmented reality, drove the need for edge computing solutions.

Today, edge computing has become a pivotal paradigm in the era of digital transformation, enabling efficient and scalable processing at the network edge. Its applications span various domains, including healthcare, transportation, manufacturing, and smart cities, revolutionizing the way data is processed, analyzed, and utilized.

By understanding the historical context of edge computing, we gain insights into its evolution and the factors that have shaped its development into a critical component of modern computing architecture.

III. KEY CONCEPTS AND TERMINOLOGY

1. Edge Computing

Edge computing refers to the practice of processing data closer to where it is generated, rather than relying solely on centralized data centers. This approach reduces latency and bandwidth usage and enables real-time processing for applications.

2. Edge Devices

Edge devices are hardware components located at the edge of a network, such as sensors, smartphones, IoT devices, and gateways. These devices collect and generate data and perform basic processing tasks before sending data to centralized servers or other edge devices.

3. Fog Computing

Fog computing extends the principles of edge computing by bringing computation, storage, and networking resources closer to the data source. Fog computing typically involves intermediate layers of computing infrastructure, such as edge gateways or fog nodes, situated between edge devices and centralized data centers.

4. Latency

Latency refers to the delay between the initiation of a data transfer and the actual transfer of data. In edge computing, minimizing latency is crucial for applications that require real-time responsiveness, such as autonomous vehicles or telemedicine.

5. Edge Analytics

Edge analytics involves performing data analysis and processing at the edge of the network, near the data source. By analyzing data locally, edge analytics can reduce the need to transmit large amounts of data to centralized servers, improving efficiency and scalability.

6. Distributed Computing

Distributed computing refers to the use of multiple interconnected computers or devices to work together on a common task. Edge computing relies on distributed computing principles to distribute processing tasks across edge devices and centralized servers.

7. Software-defined Networking (SDN)

SDN is an approach to networking that separates the control plane from the data plane, allowing network administrators to dynamically manage network resources through software. SDN plays a crucial role in enabling flexible and programmable network architectures in edge computing environments.

IV. ARCHITECTURAL MODELS

Fig. 2 Edge solutions are usually multi-layered distributed architectures encompassing and balancing the workload between the Edge layer, the Edge cloud or Edge network, and the Enterprise layer. Furthermore, when we talk about the Edge, there are the Edge devices and the local Edge servers.

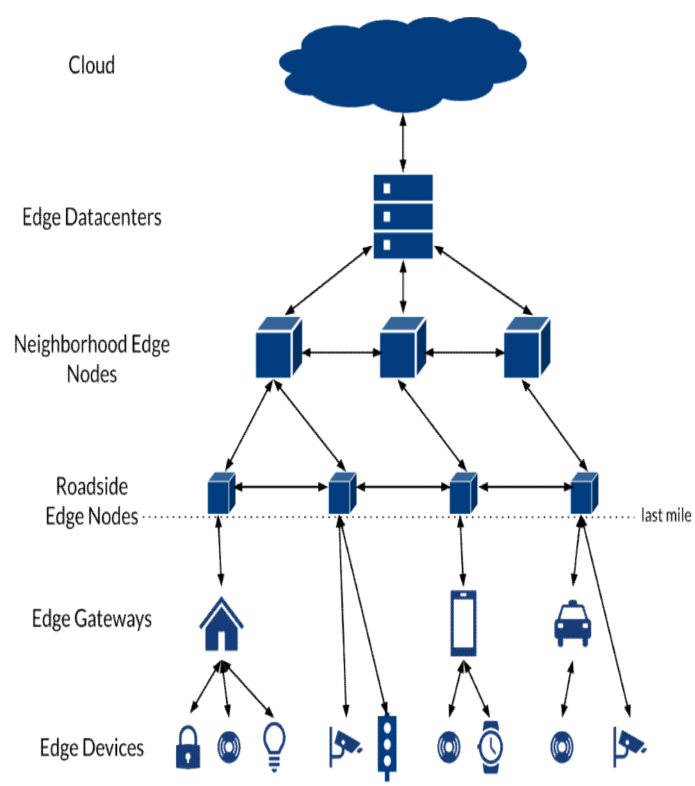

Fig. 2. Edge computing architecture overview.

Edge computing encompasses various architectural models that dictate how computing resources are distributed and organized within a network. Here, we'll explore three primary architectural models: hierarchical, flat, and hybrid.

A. Hierarchical Architecture

In a hierarchical architecture, computing resources are organized hierarchically, with multiple layers of nodes or devices. Each layer serves a specific purpose, such as data collection, processing, and storage. Data flows from edge devices to intermediate layers, such as edge gateways or fog nodes, before reaching centralized data centers. This architecture enables efficient resource allocation and scalability but may introduce additional latency due to multiple hops.

B. Flat Architecture

In a flat architecture, computing resources are deployed in a flat, decentralized manner, without distinct hierarchical layers. Edge devices communicate directly with centralized servers or with each other, bypassing intermediate layers. This architecture reduces latency by minimizing the number of hops between devices and central resources. However, managing a large number of edge devices can pose challenges in terms of scalability and resource allocation.

C. Hybrid Architecture

A hybrid architecture combines elements of both hierarchical and flat architectures to achieve a balance between efficiency and scalability. In a hybrid architecture, edge devices are organized into clusters or groups, each managed by an intermediate layer. These clusters communicate with centralized servers or other clusters, depending on the requirements of the application. This architecture offers flexibility and scalability while minimizing latency and resource overhead.

V. Technological Enablers

Several key technologies serve as the foundation for enabling edge computing solutions. These technological enablers provide the necessary infrastructure and capabilities to support distributed processing at the network edge. Let's explore some of these enablers:

1) ***Edge Servers:*** Edge servers are lightweight computing devices deployed at the network edge, closer to where data is generated. These servers are equipped with processing power, memory, and storage capabilities to handle computation-intensive tasks locally, reducing the need for data transmission to centralized data centers [2].

2) ***Edge Gateways:*** Edge gateways act as intermediaries between edge devices and centralized servers or cloud platforms. They provide connectivity, protocol translation, and data preprocessing capabilities, allowing edge devices to communicate with backend systems efficiently [3].

3) ***Edge Caching:*** Edge caching involves storing frequently accessed data or content closer to end-users or edge devices. By caching data at the network edge, edge computing systems can reduce latency and bandwidth usage, improving the overall performance of applications [4].

4) ***Software-defined Networking (SDN):*** SDN is an approach to network management that separates the control plane from the data plane, allowing network administrators to dynamically allocate and manage network resources through software. SDN enables flexible and programmable network architectures in edge computing environments, facilitating efficient data routing and traffic management [5].

5) ***Containerization and Orchestration:*** Containerization technologies, such as Docker and Kubernetes, play a crucial role in deploying and managing edge computing applications. Containers provide lightweight, isolated environments for running application components, while orchestration platforms automate the deployment, scaling, and management of containerized applications across edge nodes [6].

By leveraging these technological enablers, edge computing systems can deliver low-latency, high-performance computing services at the network edge, empowering a wide range of applications across industries.

VI. Challenge and Considerations

While edge computing offers promising benefits, it also presents several challenges and considerations that need to be addressed:

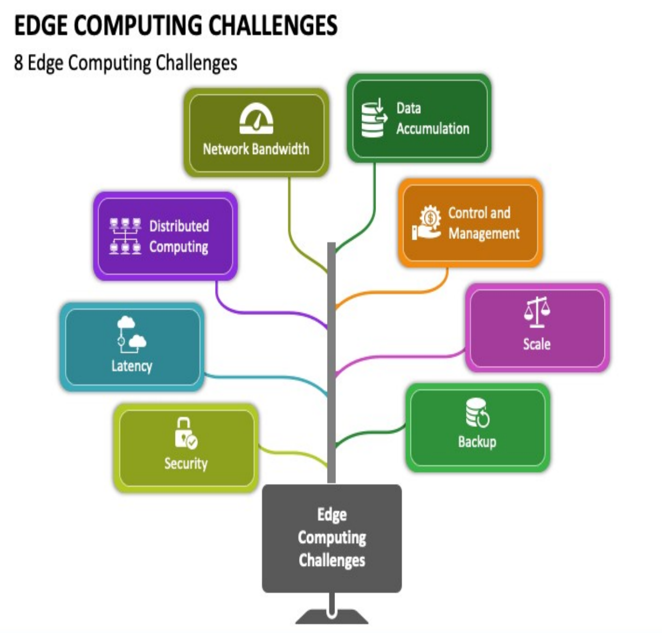

Fig. 3. Edge computing challenge

A. Latency

Latency is the delay or lag in the transmission of data between a source and a destination. In the context of edge computing, latency refers to the time it takes for data to travel from edge devices to processing nodes, be processed, and receive a response [7]. Minimizing latency is crucial for applications that require real-time or near-real-time responses, such as autonomous vehicles, augmented reality, and industrial automation [8].

Latency can be influenced by various factors, including network congestion, processing time, and distance between the edge devices and processing nodes. By bringing computation closer to edge devices, edge computing aims to reduce latency and improve the responsiveness of applications [9].

Examples:

Autonomous Vehicles: Autonomous vehicles rely on real-time data processing to make split-second decisions, such as detecting obstacles, navigating traffic, and avoiding collisions. High latency in data transmission or processing could lead to delays in decision-making, compromising the safety and efficiency of autonomous systems.

Augmented Reality (AR): AR applications overlay digital content onto the user's physical environment in real-time. Low latency is essential for providing a seamless AR experience, where digital objects must align accurately with the user's surroundings. Any delay in rendering or updating AR content can disrupt the user experience and diminish immersion.

Industrial Automation: In industrial automation systems, sensors, and actuators communicate with control systems to monitor and control manufacturing processes in real time. Latency in data transmission or processing can affect the responsiveness of control systems, leading to delays in equipment operation or quality control.

B. Security

Security is a paramount concern in edge computing due to the distributed nature of the infrastructure and the diverse range of edge devices involved. One of the primary challenges is ensuring the confidentiality, integrity, and availability of data processed at the network edge. Edge devices, such as IoT sensors or smart cameras, may lack robust security features, making them susceptible to cyberattacks and unauthorized access. For example, a compromised IoT device in a smart home network could be used as a foothold to launch attacks on other devices or gain access to sensitive personal data. Additionally, the dynamic nature of edge environments introduces challenges in maintaining security policies and enforcing access controls across distributed edge nodes. Moreover, edge computing systems often rely on wireless communication technologies, such as Wi-Fi or Bluetooth, which can be vulnerable to interception and eavesdropping attacks [8] [9]. Addressing these security challenges requires implementing robust encryption mechanisms, authentication protocols, and intrusion detection systems to protect edge devices and data from malicious threats.

C. *Privacy*

Privacy is a significant concern in edge computing environments, particularly due to the collection and processing of sensitive data at the network edge [8]. Edge devices, such as wearable health monitors or smart home assistants, often gather personal information about users' behaviors, preferences, and activities. These data may include location information, biometric data, or browsing history, raising concerns about user privacy and data protection. For example, a fitness tracker that collects GPS data to track users' running routes could inadvertently reveal their home addresses or daily routines, posing privacy risks [9]. Moreover, the distributed nature of edge computing introduces challenges in managing and securing data across multiple edge nodes, increasing the risk of unauthorized access or data breaches. To address these privacy concerns, edge computing systems must implement robust data anonymization techniques, encryption mechanisms, and privacy-preserving algorithms to safeguard sensitive information while still enabling useful insights and services [10].

D. Interoperability

Interoperability is a significant challenge in edge computing, stemming from the heterogeneous nature of edge devices, communication protocols, and data formats. The lack of standardized interfaces and communication protocols makes it challenging to seamlessly integrate diverse edge devices and platforms into cohesive ecosystems. For instance, in a smart city deployment, sensors from different manufacturers may use proprietary communication protocols, hindering interoperability and data exchange between devices [9]. Moreover, edge computing environments often involve the integration of legacy systems with modern edge technologies, further complicating interoperability efforts. Additionally, the dynamic nature of edge environments, with devices joining or leaving the network frequently, adds complexity to interoperability management. Addressing these interoperability challenges requires the development of standardized communication protocols, data models, and application programming interfaces (APIs) to enable seamless interaction and data exchange between heterogeneous edge devices and platforms [11].

E. Resource Constraints

Resource constraints pose significant challenges in edge computing environments, where edge devices often have limited computational resources, memory, and energy. These constraints can impact the performance and scalability of edge applications, especially in resource-intensive tasks such as real-time data processing or machine learning inference. For instance, IoT devices deployed in remote areas may have limited battery life, constraining the amount of processing they can perform locally [12]. Additionally, edge devices may need to operate in harsh environmental conditions, further limiting their computing capabilities. Managing and optimizing resource usage becomes crucial to ensure efficient operation and longevity of edge devices. Moreover, as the number of edge devices increases, resource contention and competition for scarce resources may arise, leading to performance degradation and bottlenecks. Addressing resource constraints requires innovative solutions such as lightweight algorithms, energy-efficient computing architectures, and dynamic resource allocation strategies to optimize resource utilization and enhance the scalability of edge computing systems [13].

F. Scalability

Scalability is a critical consideration in edge computing, particularly as the number of edge devices and applications continues to grow. One of the primary challenges is ensuring that edge computing systems can efficiently scale to accommodate increasing workloads while maintaining performance and reliability. For example, in a smart city deployment, the number of IoT sensors and actuators may rapidly expand as new applications are deployed, such as traffic monitoring or environmental sensing. Ensuring that the edge infrastructure can scale to support the influx of new devices and applications without experiencing performance degradation or resource bottlenecks is essential for meeting the evolving demands of edge computing environments. Additionally, managing and orchestrating distributed edge resources at scale poses challenges in terms of resource allocation, workload management, and fault tolerance. Dynamic scaling mechanisms, such as auto-scaling algorithms, can help optimize resource utilization and adaptively adjust the capacity of edge computing systems based on demand fluctuations. Moreover, standardized interfaces and protocols for communication and resource management are crucial for enabling interoperability and seamless integration of heterogeneous edge devices and platforms as edge environments scale [14].

Addressing these challenges and considerations requires collaborative efforts from researchers, industry stakeholders, and policymakers to develop robust solutions and standards for edge computing environments.

VII. Emerging trends

Edge computing is constantly evolving, and several emerging trends are shaping its trajectory:

A. Edge AI Integration

One of the most prominent trends is the integration of artificial intelligence (AI) capabilities at the network edge. Edge AI enables edge devices to perform complex data analytics and decision-making tasks locally, without relying on centralized cloud servers.

Edge AI is the implementation of AI platforms and solutions on the edge of a network, close to the end user's environment Edge AI deployments are typically done on devices such as edge computers, Internet of Things (IoT) hardware, and small, localized data centers.

Instead of being processed at a large, centralized data center, edge AI use cases enable AI inferences and computations to be processed on edge servers, gateways, and IoT devices deployed closer to the user. In this regard, even if Internet connectivity is unavailable, data generated by smart cameras, sensors, and similar IoT devices can still be processed within the device.

AI at the edge can be implemented on various hardware, including Central Processing Units (CPUs), Neural Processing Units (NPUs), and microcontrollers. Data are processed locally in an edge AI ecosystem, with ML models running directly in the edge devices. These edge AI/ML devices use embedded models to monitor, collect, and process device data. Businesses can then use the information to optimize business processes, correct any errors, and forecast future scenarios.

Fig. 4 and Fig. 5 compare the processing flows between traditional AI and edge AI computing applications.

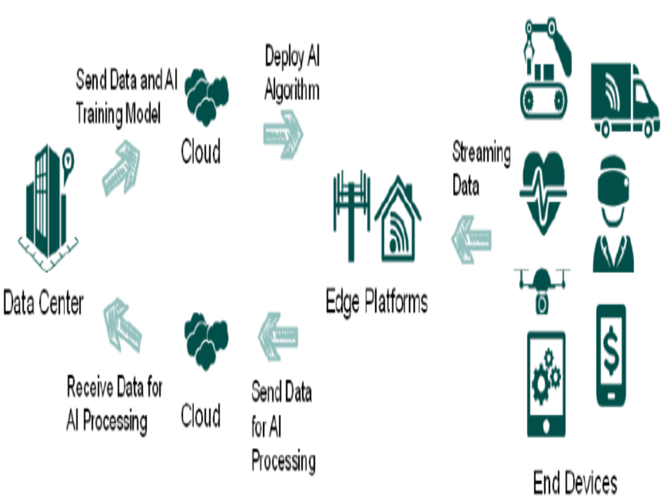

Fig. 4. Traditional AI processing flow

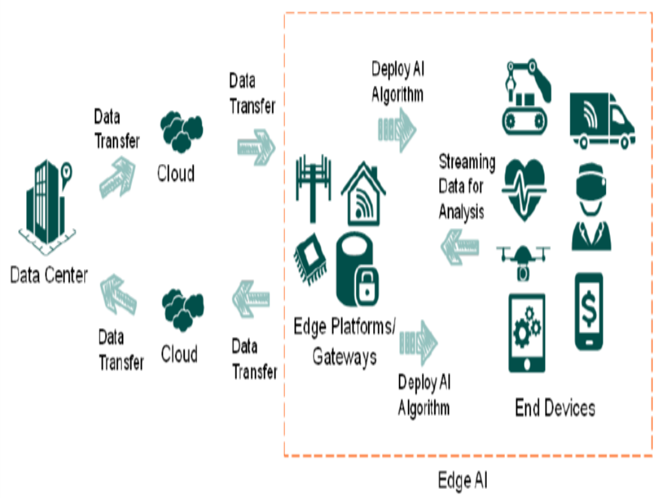

Fig.5. Processing flow for an edge AI use case.

Edge AI integration is a significant trend in edge computing, revolutionizing how data is processed and analyzed at the network edge. By embedding artificial intelligence (AI) capabilities directly into edge devices, organizations can perform advanced analytics and decision making tasks locally, without relying on centralized cloud servers [17]. This integration enables real-time insights and actions, making edge devices smarter and more autonomous. For example, in a smart surveillance system, edge AI algorithms can analyze video streams from security cameras to detect suspicious activities or identify specific objects or individuals in real time. Similarly, in autonomous vehicles, edge AI can process sensor data to detect obstacles, recognize recognize traffic signs, and make split-second decisions to

TABLE I
EMERGING TRENDS IN EDGE COMPUTING

Trend	Description
Edge AI	Integrating artificial intelligence (AI) algorithms directly onto edge devices to process data locally enables faster decision-making and reduces the need for continuous data transmission to the cloud.
5G Networks	The rollout of 5G networks enables faster data transmission and lower latency, making it more feasible to deploy edge computing solutions in various industries, such as autonomous vehicles and smart cities.
Edge-as-a-Service (EaaS)	Providing edge computing resources and services on-demand, allowing businesses to deploy and manage applications closer to the end-users without the need for extensive infrastructure investment.
Distributed Cloud	Extending cloud computing resources to the edge of the network, enabling seamless integration between cloud and edge environments, and facilitating data processing and analytics at the edge.
Edge Security and Privacy	Enhancing security measures at the edge to protect sensitive data and ensure privacy compliance, leveraging techniques such as encryption, access control, and secure device provisioning.
Edge-native Applications	Developing applications specifically optimized for edge computing environments, considering factors such as limited resources, intermittent connectivity, and varying latency requirements.
Edge Data Management	Implementing efficient data storage and processing mechanisms at the edge to manage the volume, velocity, and variety of data generated by edge devices, ensuring timely and relevant insights.
Edge Computing for IoT	Leveraging edge computing to support the massive scale and diverse requirements of IoT (Internet of Things) deployments, enabling real-time data analysis, device management, and automation.
Edge Orchestration and Automation	Utilizing orchestration and automation tools to streamline the deployment, configuration, and management of edge computing infrastructure and applications across distributed environments.
Edge Analytics and Predictive Maintenance	Employing analytics capabilities at the edge to derive actionable insights from streaming data, enabling predictive maintenance, anomaly detection, and optimization of operational processes.

ensure passenger safety [18]. Edge AI integration extends beyond traditional computing devices to include IoT sensors, drones, wearables, and more, enabling a wide range of intelligent applications across various industries.

B. Edge-Native Applications

Edge-native applications are specifically designed to run on edge computing infrastructure, leveraging the proximity to data sources and minimizing latency for real-time processing. These applications are optimized for low-latency, high-throughput processing at the network edge, offering improved performance and efficiency compared to traditional cloud-based applications. Let's delve into some examples and explore the significance of edge-native applications:

1) ***Industrial IoT Monitoring:*** In industrial IoT (IIoT) environments, edge-native applications play a crucial role in monitoring and controlling manufacturing processes in real-time. For instance, edge devices equipped with sensors can collect data on machine performance, temperature, and energy consumption directly from manufacturing equipment. Edge-native applications analyze this data locally to detect anomalies, predict equipment failures, and optimize production processes without relying on centralized cloud servers [3].

2) ***Smart City Services:*** Edge-native applications enable smart city services, such as traffic management, environmental monitoring, and public safety, to operate efficiently at the network edge. For example, in a smart traffic management system, edge devices deployed at intersections collect traffic flow data from cameras and sensors. Edge-native applications process this data locally to detect traffic congestion, optimize signal timings, and reroute vehicles in real-time, reducing congestion and improving traffic flow [19].

3) ***Healthcare Monitoring:*** In healthcare environments, edge-native applications facilitate remote patient monitoring, medical diagnostics, and personalized healthcare services. Wearable devices equipped with biosensors collect physiological data, such as heart rate, blood pressure, and glucose levels, from patients in real-time. Edge-native applications analyze this data locally to detect health anomalies, provide timely interventions, and deliver personalized healthcare recommendations without relying on cloud-based servers, ensuring privacy and reducing latency [20].

4) ***Retail Analytics:*** Edge-native applications enable retailers to enhance customer experiences, optimize store operations, and increase sales through real-time analytics. For example, edge devices deployed in retail stores capture data on customer foot traffic, product interactions, and inventory levels [21]. Edge-native applications process this data locally to generate personalized product recommendations, optimize shelf layouts, and manage inventory levels in real-time, improving operational efficiency and customer satisfaction.

By embracing edge-native applications, organizations can harness the full potential of edge computing to drive innovation, efficiency, and competitiveness across various domains.

C. Edge Orchestration Platforms

Edge orchestration platforms play a crucial role in simplifying the deployment and management of edge computing resources. These platforms provide tools and frameworks for automating the provisioning, scaling, and monitoring of edge applications and services. By streamlining edge deployment and management, orchestration platforms enable organizations to rapidly deploy and scale edge computing solutions across distributed environments.

1) ***Automated Provisioning:*** Edge orchestration platforms automate the process of provisioning edge computing resources, such as edge nodes and containers, based on predefined policies and requirements. For example, orchestration platforms can dynamically allocate resources to edge applications based on workload demands, ensuring optimal resource utilization and performance.

2) ***Scalability and Elasticity:*** Edge orchestration platforms enable organizations to scale edge computing resources in response to changing workload demands. These platforms provide mechanisms for dynamically adding or removing edge nodes and containers to accommodate fluctuating workloads, ensuring scalability and elasticity in edge deployments.

3) ***Service Discovery and Load Balancing:*** Edge orchestration platforms facilitate service discovery and load balancing across distributed edge environments. These platforms use techniques such as service registries and load balancers to efficiently route requests to edge services, ensuring high availability and fault tolerance.

4) ***Configuration Management:*** Edge orchestration platforms streamline the configuration management of edge applications and services. These platforms provide centralized tools for defining and managing configuration settings, ensuring consistency and compliance across edge deployments.

5) ***Monitoring and Analytics:*** Edge orchestration platforms offer monitoring and analytics capabilities to track the performance and health of edge applications and infrastructure. These platforms provide dashboards and alerts for real-time visibility into edge operations, enabling organizations to identify and address issues proactively.

Examples:

1) ***Kubernetes:*** Kubernetes is a popular open-source container orchestration platform widely used for managing containerized applications at scale. Kubernetes provides features such as automated deployment, scaling, and management of containerized workloads, making it well-suited for edge computing environments [22].

2) ***AWS IoT Greengrass:*** AWS IoT Greengrass is an edge computing service offered by Amazon Web Services (AWS) that extends AWS cloud capabilities to edge devices. Greengrass provides features such as local data processing, messaging, and device management, enabling organizations to run IoT applications seamlessly at the network edge [23].

D. Edge Security Enhancements

As edge computing continues to gain traction, there is a growing emphasis on enhancing security measures to protect edge devices and data from cyber threats. Several key enhancements are emerging in the realm of edge security:

1) ***Hardware-based Security:*** One of the notable enhancements is the integration of hardware-based security features into edge devices. Secure boot mechanisms, for example, ensure that only trusted firmware and software components are loaded during the boot process, preventing unauthorized tampering and malicious code injection. Additionally, hardware-based encryption modules provide robust cryptographic capabilities to protect sensitive data stored and transmitted by edge devices [24].

2) ***Edge-specific Security Frameworks:*** Another trend is the development of edge-specific security frameworks and protocols tailored to the unique requirements of edge computing environments. These frameworks define standardized security mechanisms and best practices for securing edge devices, communication channels, and data processing workflows. For instance, the Trusted Platform Module (TPM) specification defines a set of hardware-based security features that can be integrated into edge devices to enhance their security posture [25].

3) ***Edge Access Control Mechanisms:*** Access control mechanisms play a crucial role in limiting unauthorized access to edge devices and resources. Edge computing environments often implement granular access control policies to restrict access based on user roles, permissions, and authentication factors. Role-based access control (RBAC) and attribute-based access control (ABAC) are commonly used access control models that enable organizations to enforce fine-grained access policies at the edge [26].

4) ***Edge Intrusion Detection and Prevention Systems (IDPS):*** Intrusion detection and prevention systems (IDPS) are essential components of edge security architectures, providing real-time threat detection and mitigation capabilities. Edge IDPS solutions monitor network traffic, analyze system logs, and detect anomalous behavior indicative of security breaches or cyber attacks. By proactively identifying and responding to security incidents at the edge, IDPS solutions help safeguard edge environments from various cyber threats [27].

5) ***Edge Security Automation and Orchestration:*** Security automation and orchestration platforms are emerging to streamline the management and enforcement of security policies across distributed edge environments. These platforms leverage machine learning algorithms and policy-based automation to detect security vulnerabilities, remediate security incidents, and enforce compliance with regulatory requirements. By automating routine security tasks and responses, organizations can enhance the efficiency and effectiveness of their edge security operations [28].

By adopting these security enhancements, organizations can bolster the resilience of their edge computing infrastructure and mitigate the risks associated with cyber threats and data breaches.

E. *Standardization Efforts*

Standardization efforts play a crucial role in shaping the development and adoption of edge computing technologies. Several organizations and consortia are actively working towards establishing common protocols, interfaces, and architectures to promote interoperability, compatibility, and scalability across diverse edge environments.

*1) **Open Edge Computing Initiative (OECI):*** The Open Edge Computing Initiative (OECI) is one such organization dedicated to defining open standards and specifications for edge computing infrastructure and applications. OECI brings together industry stakeholders, researchers, and policymakers to collaborate on developing standardized frameworks that facilitate seamless integration and interoperability among edge devices and platforms.

*2) **Edge Computing Consortium (ECC):*** The Edge Computing Consortium (ECC) is another prominent organization driving standardization efforts in the field of edge computing. ECC focuses on defining common architectures, reference models, and protocols for edge computing deployments across various industries and use cases. By establishing standardized guidelines and best practices, ECC aims to accelerate the adoption of edge computing technologies and foster innovation in edge-enabled applications and services.

*3) **IEEE Standards Association:*** The Institute of Electrical and Electronics Engineers (IEEE) Standards Association is actively involved in developing standards for edge computing. IEEE working groups such as the P2413 Standard for an Architectural Framework for the Internet of Things (IoT) and the P1931 Standard for Fog Computing are instrumental in defining technical specifications and guidelines for edge computing architectures, protocols, and interoperability.

*4) **Examples of Standardization Efforts:*** Standardization efforts in edge computing encompass a wide range of areas, including networking protocols, data formats, security mechanisms, and application programming interfaces (APIs). For instance, standardization initiatives such as the Open Mobile Alliance (OMA) Lightweight M2M (LwM2M) protocol and the Internet Engineering Task Force (IETF) Constrained Application Protocol (CoAP) address the need for lightweight, efficient communication protocols for edge devices in IoT deployments.

*5) **Benefits of Standardization:*** Standardization in edge computing offers several benefits, including improved interoperability, reduced development costs, faster time-to-market, and enhanced scalability. By adhering to standardized protocols and interfaces, organizations can ensure seamless integration and compatibility between heterogeneous edge devices and platforms, facilitating the deployment and management of edge computing solutions across diverse environments.

By staying abreast of these emerging trends, organizations can harness the full potential of edge computing to drive innovation, efficiency, and competitiveness in various domains.

VII. USE CASES AND APPLICATIONS

Edge computing has a wide range of applications across various industries, enabling real-time processing, low-latency communication, and improved efficiency. The integration of edge computing into daily workflows and applications presents a plethora of opportunities for businesses. We have categorized the potential applications of edge computing into five significant industries, including smart cities, healthcare, manufacturing, autonomous vehicle, and retail, and highlighted the diverse possibilities within these industries. Let's explore some prominent use cases and applications of edge computing:

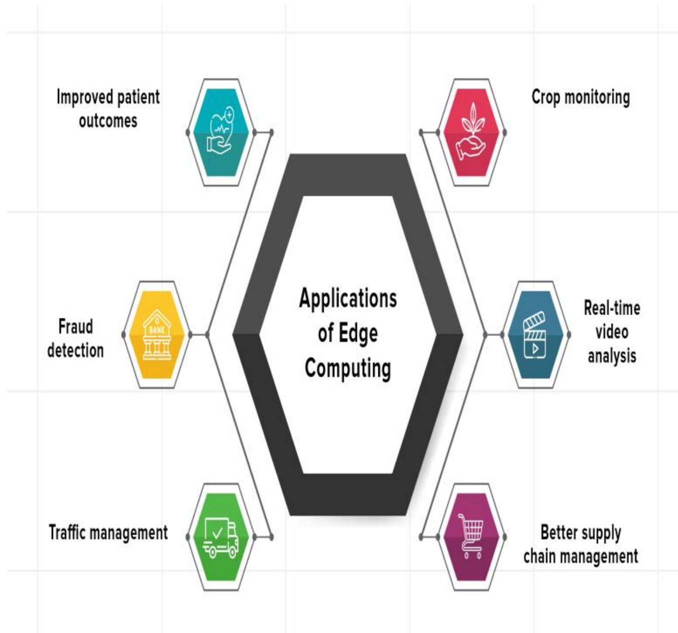

Fig. 6. Applications of edge computing

A. Smart Cities

Smart cities leverage technology, including edge computing, to improve the quality of life for residents, enhance sustainability, and optimize urban infrastructure. Here are some key aspects and examples of smart cities:

*1) **Traffic Management:*** Edge computing enables real-time analysis of traffic data from sensors, cameras, and GPS devices to optimize traffic flow and reduce congestion. For example, edge devices can detect traffic jams, adjust traffic signals dynamically, and provide alternate routes to drivers, improving overall traffic efficiency [31].

*2) **Public Safety:*** Smart cities use edge computing to enhance public safety through video surveillance, gunshot detection systems, and emergency response optimization. Edge devices can analyze video feeds in real-time to detect suspicious activities, identify license plates, and alert law enforcement agencies to potential threats, enhancing the city's security infrastructure [32].

*3) **Environmental Monitoring:*** Edge computing facilitates environmental monitoring initiatives in smart cities by collecting and analyzing data on air quality, temperature, humidity, and noise levels. For instance, edge devices deployed throughout the city can detect pollution hotspots, monitor weather patterns, and provide early warnings for natural disasters, helping city officials make informed decisions to protect the environment and public health [33].

*4) **Energy Management:*** Edge computing enables smart energy management solutions in cities by optimizing energy consumption, monitoring utility usage, and integrating renewable energy sources. Edge devices installed in buildings can regulate heating, ventilation, and air conditioning (HVAC) systems based on occupancy levels and weather conditions, reducing energy waste and lowering utility bills. Additionally, edge computing facilitates the integration of solar panels, wind turbines, and smart grids into the city's energy infrastructure, promoting sustainability and resilience [34].

*5) **Waste Management:*** Smart cities leverage edge computing to improve waste management processes by deploying smart bins equipped with sensors and actuators. Edge devices in these bins can monitor waste levels, detect anomalies, and optimize collection routes in real-time, reducing costs and minimizing environmental impact. Furthermore, edge computing enables predictive maintenance of waste collection vehicles, ensuring they are deployed efficiently and reducing downtime [35].

These examples illustrate how edge computing is transforming cities into smarter, more efficient, and sustainable urban environments, enhancing the quality of life for residents and driving economic growth.

B. Healthcare

Edge computing is revolutionizing healthcare by enabling real-time monitoring, data analysis, and personalized patient care. Here are some key applications of edge computing in healthcare:

*1) **Remote Patient Monitoring:*** Edge computing allows for continuous monitoring of patients' vital signs and health parameters in real-time, even outside traditional healthcare settings. Wearable devices equipped with sensors can collect data such as heart rate, blood pressure, and glucose levels, and process this information locally at the edge. Healthcare providers can then receive alerts or notifications in case of abnormal readings, allowing for timely intervention and proactive management of chronic conditions [32].

*2) **Telemedicine and Virtual Consultations:*** Edge computing facilitates telemedicine and virtual consultations by providing high-quality video conferencing and remote diagnostic capabilities. Edge devices installed in patients' homes or in ambulances can capture and transmit patient data securely to healthcare professionals located at remote locations. This enables timely consultations, diagnosis, and treatment planning, particularly for patients in rural or underserved areas with limited access to healthcare facilities [36].

*3) **Emergency Response and Disaster Management:*** Edge computing plays a crucial role in emergency response and disaster management scenarios by providing real-time communication and decision support capabilities. Edge devices deployed in ambulances, field hospitals, and emergency shelters can process data from multiple sources, such as patient monitors, medical records, and geographic information systems (GIS). This enables emergency responders to triage patients, allocate resources efficiently, and coordinate rescue efforts effectively, even in challenging environments with limited connectivity [37].

*4) **Health Data Analytics and Predictive Modeling:*** Edge computing enables healthcare organizations to analyze large volumes of health data in real-time and derive actionable insights to improve patient outcomes and operational efficiency. Edge devices equipped with machine learning algorithms can analyze electronic health records (EHRs), medical imaging data, and genomic data locally, without relying on centralized servers. This facilitates early detection of diseases, personalized treatment plans, and predictive modeling for population health management [38].

*5) **Drug Delivery and Medication Management:*** Edge computing supports smart drug delivery systems and medication management solutions by ensuring timely and accurate administration of medications. Edge devices embedded in smart pill bottles or wearable drug delivery devices can monitor medication adherence, track patient responses to treatment, and provide reminders or alerts as needed. This enhances medication safety, reduces medication errors, and improves patient adherence to prescribed regimens [39].

These examples illustrate how edge computing is transforming healthcare delivery by enabling personalized, proactive, and efficient patient care.

C. Manufacturing

In manufacturing environments, edge computing enables predictive maintenance, process optimization, and quality control. Edge devices installed on machinery can analyze sensor data in real time to identify potential equipment failures before they occur, minimizing downtime and maximizing productivity. Additionally, edge computing facilitates collaborative robots (cobots) that work alongside human workers, enhancing efficiency and safety on the factory floor. Let's explore how edge computing is revolutionizing the manufacturing industry:

*1) **Predictive Maintenance:*** Edge computing enables manufacturers to implement predictive maintenance strategies, reducing downtime and improving equipment reliability. By analyzing sensor data from machinery and equipment in real-time, edge devices can detect anomalies and predict potential failures before they occur. For example, a manufacturing plant can use edge devices to monitor the temperature, vibration, and performance of industrial machinery, identifying signs of wear or malfunction and scheduling maintenance proactively to avoid costly downtime [40].

*2) **Process Optimization:*** Edge computing facilitates process optimization by providing real-time insights into manufacturing operations. Edge devices collect and analyze data from sensors, PLCs (Programmable Logic Controllers), and MES (Manufacturing Execution Systems) to identify inefficiencies and bottlenecks in production processes. For instance, edge analytics can optimize production line scheduling, adjust machine settings based on environmental conditions, and minimize material waste, leading to improved productivity and cost savings [41].

*3) **Quality Control:*** Edge computing enhances quality control processes by enabling real-time monitoring and analysis of product quality. Edge devices equipped with sensors and vision systems can inspect products on the production line for defects or deviations from quality standards. If a defect is detected, edge devices can trigger corrective actions, such as adjusting machine parameters or diverting faulty products for inspection or rework. By detecting and addressing quality issues early in the manufacturing process, edge computing helps ensure that only high-quality products reach the market, enhancing customer satisfaction and brand reputation [42].

*4) **Collaborative Robots (Cobots):*** Edge computing enables the deployment of collaborative robots, or cobots, in manufacturing environments. Cobots work alongside human workers, assisting with repetitive or dangerous tasks and enhancing productivity and safety on the factory floor. Edge devices equipped with machine learning algorithms enable cobots to adapt to changing conditions in real-time, making them ideal for tasks that require flexibility and agility. For example, cobots can assist with assembly tasks, material handling, and quality inspection, freeing up human workers to focus on more complex and value-added activities [43].

*5) **Supply Chain Optimization:*** Edge computing extends its benefits to supply chain management, enabling real-time visibility and optimization of supply chain processes. Edge devices deployed at distribution centers, warehouses, and transportation hubs collect and analyze data on inventory levels, order fulfillment, and logistics operations. By providing real-time insights into supply chain performance, edge computing helps manufacturers optimize inventory levels, minimize lead times, and streamline logistics operations, resulting in improved efficiency and customer satisfaction [44].

These examples demonstrate how edge computing is transforming the manufacturing industry by enabling predictive maintenance, process optimization, quality control, collaborative robotics, and supply chain optimization.

D. Autonomous Vehicles

Autonomous vehicles (AVs) represent a groundbreaking application of edge computing, leveraging real-time data processing and decision-making to navigate safely and efficiently. AVs rely on a myriad of sensors, such as cameras, LiDAR, radar, and GPS, to perceive their surroundings and make driving decisions. Edge computing plays a crucial role in AVs by enabling onboard processing of sensor data, reducing reliance on centralized data centers and minimizing latency in decision-making [45]. For example, edge devices installed in AVs can analyze sensor data in real-time to detect obstacles, recognize traffic signs, and predict the behavior of other vehicles on the road. By processing data locally at the edge, AVs can react quickly to changing traffic conditions, ensuring smooth and safe operation.

Moreover, edge computing enables AVs to communicate with nearby vehicles and infrastructure through vehicle-to-everything (V2X) communication technologies [46]. For instance, AVs can exchange information about road conditions, traffic congestion, and potential hazards with neighboring vehicles and roadside sensors, allowing them to anticipate and avoid potential accidents proactively.

Additionally, edge computing facilitates over-the-air (OTA) updates and software patches for AVs, enabling continuous improvements in performance and safety without requiring vehicles to return to centralized maintenance facilities [47]. This capability is essential for ensuring that AVs remain up-to-date with the latest software and security patches, enhancing their reliability and resilience to cyber threats.

Fig. 7. Edge computing-based autonomous vehicles

Overall, the integration of edge computing with autonomous vehicles promises to revolutionize transportation systems, making roads safer, reducing traffic congestion, and improving the overall driving experience.

E. Retail

In retail environments, edge computing enables personalized customer experiences, inventory management, and supply chain optimization. For example, edge devices in stores can analyze customer behavior in real-time, recommend products based on purchase history, and manage inventory levels to prevent stockouts. Additionally, edge computing facilitates cashier-less checkout systems, allowing customers to pay for items using their mobile phones without waiting in line. Here's how edge computing is reshaping the retail industry:

*1) **Personalized Customer Experiences:*** Edge computing enables retailers to deliver personalized experiences to customers in real-time. By analyzing customer data, such as purchase history and browsing behavior, at the edge, retailers can offer tailored product recommendations and promotions through mobile apps or digital signage in-store. For example, a customer browsing the shoe section may receive personalized discounts on sneakers based on their preferences and purchase history.

*2) **Inventory Management:*** Edge computing facilitates real-time inventory management, helping retailers optimize stock levels and prevent stockouts. Edge devices installed in warehouses and stores continuously monitor inventory levels and automatically place orders when stock runs low. Additionally, edge analytics can identify slow-moving or obsolete inventory, enabling retailers to make data-driven decisions to optimize their product assortment and pricing strategies.

*3) **Cashier-less Checkout:*** Edge computing powers cashier-less checkout systems, allowing customers to scan and pay for items using their mobile phones without waiting in line. By processing transactions locally at the edge, retailers can reduce checkout times and improve customer satisfaction. For instance, Amazon Go stores use computer vision and sensor fusion technologies at the edge to track items taken by customers and automatically charge their accounts upon exit.

*4) **Enhanced In-Store Experiences:*** Edge computing enhances in-store experiences by enabling interactive displays, augmented reality (AR) experiences, and smart shelves. For example, interactive displays can provide product information, recommendations, and reviews to shoppers, while AR experiences allow customers to visualize how furniture or clothing will look in their homes before making a purchase. Smart shelves equipped with RFID tags and sensors can detect when items are removed or restocked, providing real-time visibility into inventory levels and product availability.

*5) **Supply Chain Optimization:*** Edge computing optimizes supply chain operations by enabling real-time tracking and monitoring of shipments, delivery vehicles, and warehouse operations. By integrating edge devices with logistics management systems, retailers can streamline transportation routes, reduce delivery times, and improve order fulfillment accuracy. For example, Walmart uses edge computing and IoT sensors to monitor the temperature of perishable goods during transportation, ensuring food safety and quality compliance.

These examples demonstrate how edge computing is transforming the retail industry, enabling retailers to deliver seamless omnichannel experiences, optimize operations, and stay competitive in a rapidly evolving market landscape.

VIII. Open challenges and future works

While edge computing holds great promise, several challenges remain to be addressed for its widespread adoption and continued advancement. One of the key challenges is security. As edge devices proliferate and data is processed closer to the edge, ensuring the security and privacy of sensitive information becomes increasingly complex. Addressing security concerns, such as data breaches, unauthorized access, and malicious attacks, requires robust encryption mechanisms, authentication protocols, and intrusion detection systems tailored for edge environments.

Another significant challenge is interoperability. With the diversity of edge devices, platforms, and communication protocols, achieving seamless interoperability and integration poses a considerable hurdle. Standardization efforts and open-source initiatives play a crucial role in establishing common frameworks and protocols to enable interoperability among heterogeneous edge systems.

Scalability is also a pressing concern as the number of edge devices and applications continues to grow. Edge computing systems must be able to scale dynamically to accommodate increasing workloads while maintaining performance and reliability. Efficient resource management, auto-scaling mechanisms, and distributed orchestration platforms are essential for ensuring the scalability of edge environments.

Looking towards the future, several exciting directions emerge for edge computing. Edge AI, the integration of artificial intelligence algorithms and models directly into edge devices, holds immense potential for enabling intelligent decision-making and real-time analytics at the network edge. Edge-native applications optimized for low-latency, high-throughput processing are expected to proliferate, catering to diverse use cases across industries.

Moreover, advancements in edge orchestration, edge-native databases, and edge-to-cloud integration are poised to drive innovation and efficiency in edge computing. As edge computing continues to evolve, interdisciplinary collaboration, research, and innovation will be vital in addressing existing challenges and unlocking new possibilities for edge-enabled applications and services.

In conclusion, while edge computing faces several challenges, its future looks promising with ongoing advancements, innovations, and collaborative efforts aimed at realizing its full potential in reshaping the landscape of computing.

Acknowledgment

I would like to express my sincere gratitude to all those who have contributed to the completion of this survey paper on edge computing. Firstly, I extend my heartfelt thanks to my Prof. Dai Penglin for their guidance, encouragement, and valuable feedback throughout the research process. Their support has been instrumental in shaping the direction and content of this paper. I also want to acknowledge the researchers, scholars, and practitioners whose work and insights have informed and enriched the discussions presented in this paper. Additionally, I am grateful to my colleagues and friends for their encouragement and assistance during the writing process. Lastly, I wish to thank my family for their unwavering support and understanding throughout this endeavor. Their love and encouragement have been a source of motivation and strength.

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