Human-Centric AI-Enabled Extended Reality Reference Architecture for Industry 5.0*

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Abstract— **Industry 5.0 improves human-machine collaboration by integrating Artificial Intelligence (AI) and Extended Reality (XR) into industrial environments. This paper presents a structured Reference Architecture for a system that addresses industrial environments within the Industry 5.0 paradigm, iteratively refined based on evolving business and technical requirements. Designed for scalability, interoperability, and flexibility, it enables seamless interaction between XR applications, AI-powered decision support tools, and industrial systems. The architecture incorporates an enterprise architecture perspective that addresses industry-driven use cases and user scenarios from six pilot applications. Key components, including XR applications, AI recognition models, digital twins (DTs), and an orchestration hub, are outlined. The business layer is built on user stories that reflect real-world industrial needs from various sectors, and future directions for extending the architecture within Industry 5.0 ecosystems are discussed.**

I. INTRODUCTION

As industries shift towards advanced, sustainable, and human-centric practices, Industry 5.0 emerges as a transformative paradigm integrating AI and human collaboration to enhance capabilities and place humans at the center [1]. While interpretations of Industry 5.0 vary [2], most emphasize human-technology synergy to build resilient and adaptable industrial processes. AI and XR play a crucial role in boosting efficiency, flexibility, and agility to meet evolving market demands [3].

The increasing interconnectivity in manufacturing demands a structured reference architecture to manage complexity [4]. This architecture must ensure interoperability, scalability, and seamless integration of cutting-edge technologies, such as Gen AI (Generative AI), Explainable AI (XAI), Neurosymbolic AI, and XR for innovative workforce training.

However, key challenges include integrating diverse data sources (XR feedback, sensors, **Enterprise Resource Planning (ERP)** data, AI training data), developing human digital twins for personalized training, and orchestrating multiple XR applications. Addressing these challenges requires a cohesive architectural framework.

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This paper proposes a reference architecture for Industry 5.0, integrating AI and XR technologies to enhance industrial training and human-centric manufacturing. Section II reviews Industry 4.0 architectures. Section III details the proposed reference architecture, covering enterprise modeling with ArchiMate [5] and presenting its three-layer structure: Business Layer, Application Layer, and Technology Layer. Section IV evaluates the reference architecture, discussing its strengths, scalability and alignment with Industry 5.0 principles while addressing challenges and exploring relevant use cases. Finally, Section V summarizes key contributions and outlining future research directions.

II. RELATED WORK

The shift from Industry 4.0 to Industry 5.0 emphasizes human-centric, sustainable, and resilient manufacturing. While various Industry 4.0 architectures exist, integrating AI, XR, and DTs for enhanced human-machine collaboration remains an open research area [6]. To our knowledge, no Reference Architecture fully addresses Industry 5.0's diverse use cases. This section reviews existing architectural efforts in smart manufacturing and outlines the challenges the proposed reference architecture aims to address. Notably, broader standards such as RAMI4.0 [7], ETSI [8], and IIRA [9] are beyond the scope of this review.

Reference architectures are crucial in designing complex systems, ensuring consistency, scalability, and efficiency. Various studies have explored reference architectures and intelligent system design. In [10], the authors discuss reference architecture principles, including description, instantiation, and evaluation. Similarly, [11] applies these concepts to Learning Management Systems, while [12] focuses on intelligent control systems, introducing the **Real-time Control System (RCS)** reference model for real-time decision-making. However, these works do not address Industry 5.0's unique challenges, which demand human-centric and adaptive features.

In the **Industrial Internet of Things (IIoT)**, Bader's study [13] reviews existing reference architectures and proposes a Linked Data-based knowledge graph to structure information across IIoT frameworks. While insightful, it overlooks critical Industry 5.0 aspects, such as human-centricity and adaptability.

Similarly, [14] and [15] propose **Internet of Things (IoT)** and IIoT architectures for Industry 4.0, focusing on **Cyber-Physical Systems (CPS)** and AI-driven automation but do not address Industry 5.0 concepts like sustainability and

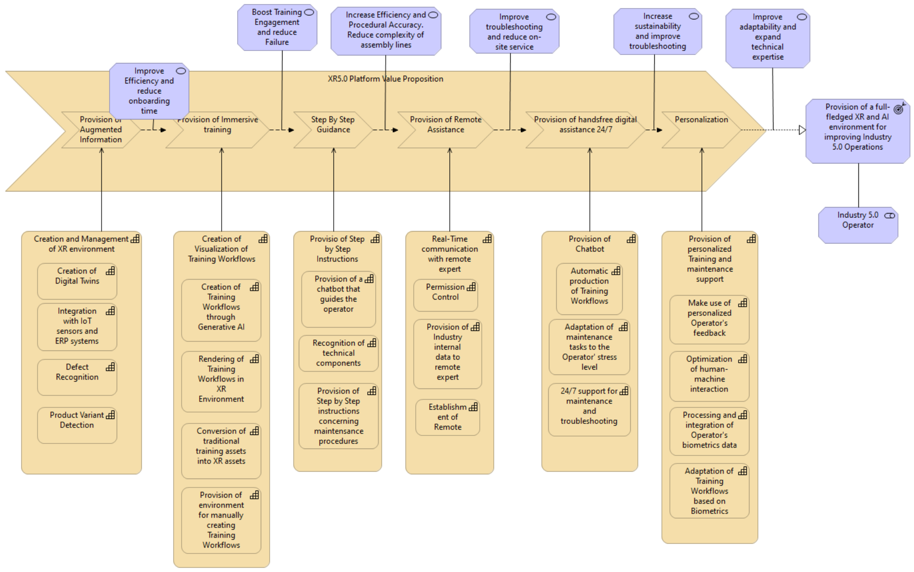

Fig. 1. Vision of the Reference Architecture (Value Stream - Strategy layer)

adaptability. Additionally, [4] reviews existing architectures but does not introduce a new reference model for Industry 5.0.

In AI and machine learning, [16] reviews **Machine Learning Operations (MLOps)** and presents a reference architecture for **Machine Learning (ML)** deployment but does not consider its integration within Industry 5.0 frameworks. In smart manufacturing, [17] and [18] address automation and efficiency in Industry 4.0 but focus mainly on machine-centric solutions, not human-centricity or sustainability.

The work in [19] shares similarities with ours, designing an architecture for Industry 4.0 using enterprise architecture principles, leveraging ArchiMate for RAMI4.0. However, it does not address Industry 5.0 concepts, such as resilience, sustainability, and human-centricity.

This paper proposes an Industry 5.0 architecture that prioritizes human-centric manufacturing by integrating AI and XR. Unlike previous works focused on IoT, MLOps, or Industry 4.0, our approach directly addresses human-machine collaboration. The reference architecture, developed through the user stories of six diverse pilots, provides a flexible and scalable solution, incorporating AI-driven decision-making and XR for enhanced user interaction. By tackling these challenges, our architecture extends prior frameworks with a holistic, adaptable design for real-world Industry 5.0 applications.

III. Proposed Reference Architecture for Industry 5.0

Enterprise Architecture aligns business goals, application systems, and technology infrastructure to achieve strategic objectives. This paper uses Enterprise Architecture to design a framework integrating AI and XR within Industry 5.0. The design follows the **Open Group Architecture Framework (TOGAF) Architecture Development Framework (ADM)** [20] and utilizes ArchiMate, a modeling language that facilitates clear communication across business, application, and technology layers. The layered approach includes viewpoints like organizational roles and value streams. The Business Layer defines value-delivering services, the Application Layer covers supporting software systems, and the Technology Layer addresses infrastructure for deployment. This framework ensures seamless integration and flexibility for addressing complex challenges.

This chapter presents the Enterprise Architecture of the proposed system, starting with a high-level vision, followed by detailed exploration of the Business, Application, and Technology layers and their interactions in Industry 5.0.

A. *Vision of the Architecture*

The architecture aligns with Industry 5.0 strategic objectives, ensuring efficient value delivery to all stakeholders. The architectural vision provides a high-level overview of key processes, capabilities and technologies working together to achieve the desired outcomes. The value stream diagram included in this section illustrates how value is created and delivered, offering a clear understanding of the flow of activities and the enabling capabilities. To this end, the value stream diagram is a critical tool that visualizes:

- The stages where value is created or transformed within the system.
- The system's capabilities and resources required at each stage.
- The flow of value from initial inputs to final delivery to stakeholders.

By providing a holistic view, the diagram ensures that the architecture remains focused on delivering value efficiently and effectively. As shown in Fig.1 , the value stream diagram consists of 6 stages that deliver different values (e.g. efficiency improvement, failure reduction, etc.) through certain

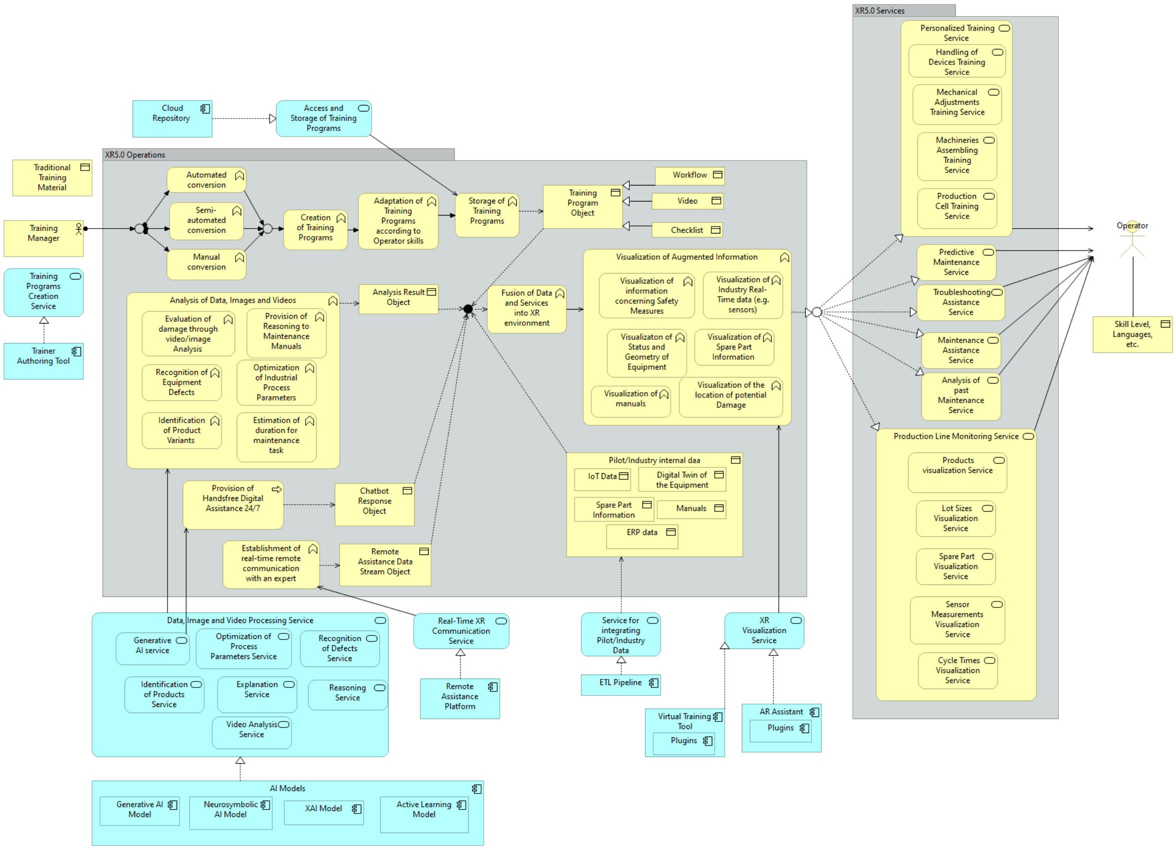

Fig. 2. Business Layer of the Architecture

activities (e.g. provision of augmented information, provision of immersive training, etc.)

The vision of the architecture provides a clear direction on how it can deliver value, ensuring alignment between strategic goals, operational processes and the technologies supporting human-centric industrial frameworks.

B. Architectural Layers

The reference architecture is structured using a layered approach, aligning with the principles of the ArchiMate framework. This approach ensures clarity, modularity and consistency across the various aspects of the system, allowing stakeholders to easily understand and analyze the relationships between needs, application capabilities and technological infrastructure. The layers in this architecture serve distinct but interconnected purposes:

1) Business Layer: The business layer of the architecture presents the foundational services and workflows that empower the operator in an Industry 5.0 environment, leveraging cutting-edge XR and AI technologies. This layer bridges the needs of industrial operators with advanced technological solutions, ensuring efficient training, maintenance, and production monitoring. As shown in Fig. 2 the business layer is enabling the operator to perform tasks more effectively through enhanced visualization, real-time assistance, and streamlined data integration.

At the heart of the business layer lies the Visualization of Augmented Information function, which synthesizes and displays critical industrial data to the operator through XR glasses. This function supports a variety of sub-functions, such as visualizing real-time sensor data, safety measures, equipment geometry, spare part details, manuals, and potential damage locations. These capabilities are powered by the integration of diverse industrial data sources, represented collectively as the Pilot/Industry Internal Data, which includes IoT data, DTs, ERP information, and more.

The Fusion of Data and Services into XR Environment function plays a pivotal role, acting as a junction where multiple workflows converge. These workflows ensure that the operator is equipped with accurate and up-to-date information. Inputs to this fusion process include training workflows, analysis results derived from AI-driven image and video processing, chatbot responses for 24/7 digital assistance, and real-time data streams from remote communication with experts. Together, these inputs enable a seamless and immersive XR experience for the operator.

Supporting this ecosystem are a range of business services that cater to the operator's key tasks. For instance, the Personalized Training Service delivers tailored training programs, covering areas like device handling, mechanical adjustments, and production cell operations. The Maintenance Assistance Service and related services provide proac-

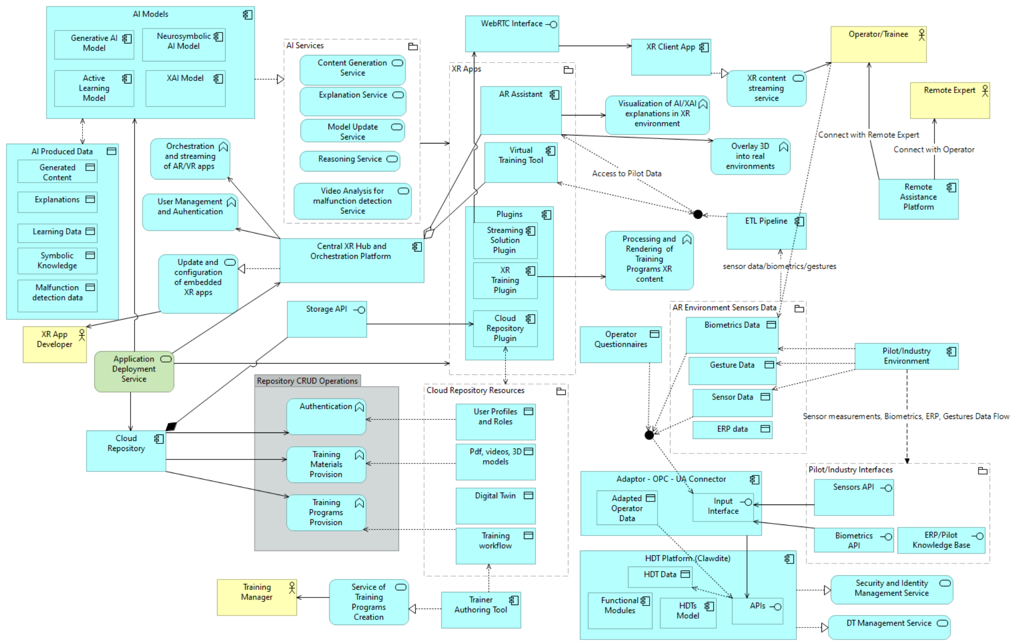

Fig. 3. Application Layer of the Architecture

tive and reactive support for industrial equipment, while the Production Line Monitoring Service offers insights into product visualization, cycle times, and sensor measurements. These services collectively ensure that the operator has the tools and knowledge needed for effective decision-making.

The business layer is not isolated but tightly integrated with the underlying application layer. Key application components like the Trainer Authoring Tool, Cloud Repository, AI Models, and the **Extract, Transform, Load (ETL)** Pipeline provide the technological backbone that realizes the necessary business services. For example, the Trainer Authoring Tool facilitates the creation of training workflows, while the Cloud Repository ensures storage and access to training materials. Similarly, the AI Models application component powers the analysis of data, enabling predictive maintenance and optimized industrial processes.Finally, the inclusion of services like Real-Time XR Communication ensures that operators can connect with remote experts for collaborative troubleshooting, leveraging XR for effective guidance.

This business layer is a dynamic and interconnected framework that aligns industrial operations with state-of-the-art technological advancements. By focusing on visualization, real-time assistance, and seamless integration of data and services, it lays the groundwork for achieving the goals of Industry 5.0—enhancing human-machine collaboration and ensuring sustainable, efficient, and human-centric industrial practices.

2) Application Layer: The Application Layer defines software components that support business and technology operations, including application services, data objects, interfaces, and their relationships. As shown in Fig.3, this layer integrates AI models, XR applications, cloud resources, and supporting platforms to provide intelligent, interactive solutions.

The key elements and their roles are summarized below:

- AI Models and Services:The AI Models application component consists of four specialized models: The Gen AI, Neurosymbolic AI, Active Learning and XAI Models. The AI models realize services such as: content generation, AI model explanations, malfuction detection data, object recognition, etc. All these AI services are consumed by the corresponding XR application.
- XR applications and the Central XR Hub: XR applications is a grouping element that integrates various plugins and application components for immersive content creation and streaming. Key components include: (i) the streaming solution plugin which streams XR content enabling rendering on the server, (ii) the cloud repository plugin which facilitates retrieval from the cloud repository application component, (iii) the XR training plugin which is used for the visualization of training programs and (iv) the **Augmented Reality (AR)** assistant and the virtual training tool which are indicative XR applications. It has to be noted that all XR applications are orchestrated by the central XR Hub which also provides user management and authentication.
- Cloud Repository and Training Management: The Cloud Repository serves as a central storage and retrieval platform. It stores training materials and training programs, and it exposes the **Application Programming Interface (API)** “Storage API”. Through this interface, the Cloud Repository plugin is able to retrieve the content of the repository which comprises PDFs, videos, 3D models and training workflows. Moreover,

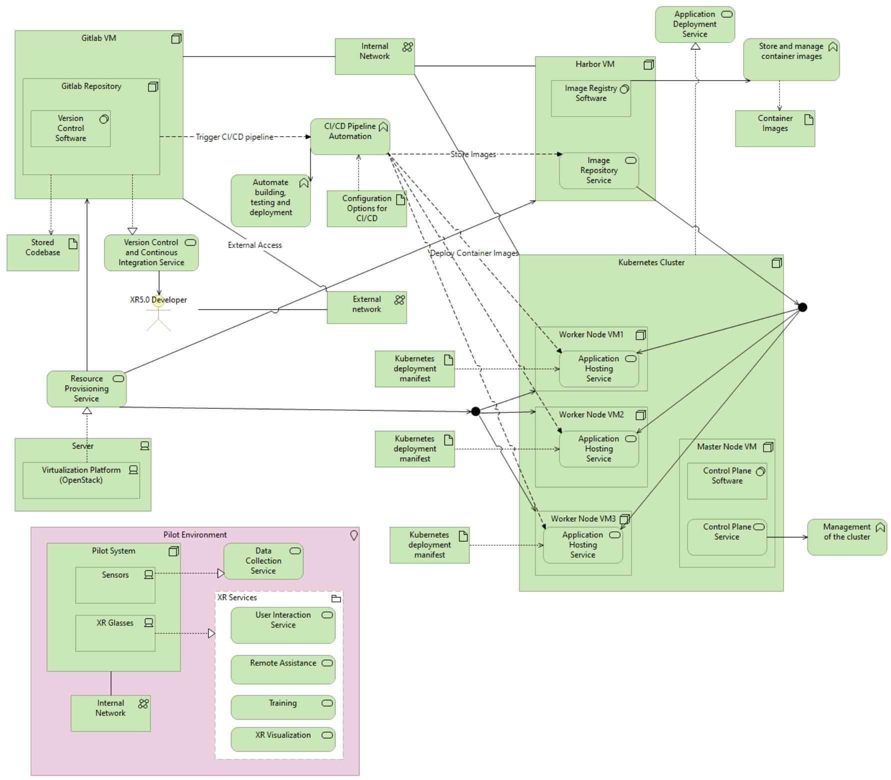

Fig. 4. Technology Layer of the Architecture

as shown in figure 21, the training workflows are authored by the Trainer Authoring Tool which is a web application used by the training manager of Industry 5.0.

- Pilot Environment and Sensor Data Integration: Through pertinent interfaces, the ETL pipeline tool acts as a data pipeline tool, accesses the industry data (sensors, XR gesture data, ERP data, etc.), transform them in a suitable format and deliver the harmonised data to the XR applications for visualization purposes through the XR glasses.
- Remote Assistance Platform: Finally, as shown in the figure below, the reference architecture includes a Remote Assistance Platform application component that enables communication between the operator and a remote expert. This enables real-time assistance through XR technologies, enhancing operational support and troubleshooting.

As a result, the Application Layer establishes a robust and interconnected architecture to deliver advanced AI-driven XR experiences. By integrating AI models, XR applications, cloud-based repositories and remote assistance capabilities, the design supports interactive operator training, maintenance and decision-making processes. Each component is carefully orchestrated to ensure scalability, seamless integration and alignment with overall objectives.

3) Technology Layer: The Technology Layer defines the infrastructure services and physical or logical components that support application and business processes. This layer describes elements such as devices, nodes, system software, networks, and their relationships, providing a foundation for higher layers in the enterprise architecture. In this context, the Technology Layer illustrates the system's virtualized infrastructure and network connectivity, which supports DevOps practices and automated deployment pipelines.

As shown in Fig.4, the key components of this layer are the following:

- Physical Server and Virtualization Layer: At least one physical server device has to be provided in order to host the system's resources. This server represents the underlying hardware.
- Virtual Machines (VMs): Several VMs are provisioned on the virtualization platform to support the GitLab, the image registry and the cluster that runs the applications.
- Communication Networks: There is the internal network that connects all VMs hosted on the server and there is also the internal network in the pilot environment which ensures isolation of the industry systems and the operator devices (ERP, sensors, databases, machines, etc.). There is also the external network which enables partners from external organizations to connect to the GitLab VM securely.
- Key Data Flows and Processes: At first, the developers push their code to the shared GitLab. Then the code from the repository is processed through GitLab **Continous Integration/Continous Delivery (CI/CD)** pipelines, producing container images stored in the Harbor image registry. Then, the Kubernetes master

node pulls images from Harbor and deploys them to the worker nodes, using the internal network for communication. Finally, in the pilot settings, the operator will use both the deployed applications hosted in Kubernetes worker nodes but also their internal application and services which are internally deployed in order to perform their operations.

The Technology Layer for the system effectively balances resource provisioning, secure networking and automation to meet the system's requirements for **Development and Operations (DevOps)** and artifact deployment. This architecture provides a robust foundation for the system's operations, ensuring efficiency, security and scalability.

IV. Evaluation, Discussion and Use Cases

The proposed Reference Architecture addresses key challenges of Industry 5.0 by integrating AI-driven automation and XR technologies into a unified framework. Its main strength is its adaptability to diverse use cases across sectors and it is being validated in six heterogeneous pilots: (i) Rapid Human-Centric AI-Enabled Product Design", (ii) Human-Centered Remote Maintenance and Asset Management, (iii) Operator 5.0 Training for Smart Water Pipes based on XR Streaming, (iv) Worker-Centric Aircraft Maintenance Training, (v) Increased Effectiveness and Safety of Product Assembly and Repair Processes and (vi) Human-Centric Guidance and Troubleshooting for Customer Service.

However, several challenges remain. While the architecture provides a clear structure, real-world implementation may face constraints such as compatibility with legacy systems and varying levels of digital maturity. The seamless integration of AI and XR introduces complexities related to data processing, security, and computational efficiency, especially in real-time environments. Additionally, the system's adoption requires skilled personnel for effective operation.

V. Conclusion and Future Work

This paper presented a novel reference architecture for Industry 5.0, integrating AI and XR to potentially enhance interoperability and support a human-centric, resilient industrial paradigm. Unlike previous works focused solely on automation, this approach might emphasize human-intelligent system collaboration, potentially enabling more adaptable and efficient environments.

Future work could explore validating the architecture through more pilot implementations across different sectors. Additionally, efforts may focus on refining the integration of AI and XR, addressing challenges related to data security, edge computing, and adaptive behavior. Expanding the evaluation framework with performance benchmarks and user feedback could provide deeper insights into the architecture's impact, ensuring scalability and adaptability for Industry 5.0 applications.

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