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A Practical Approach to Industrial Digitalization through Data Acquisition and Systems Integration for Predictive Maintenance

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Abstract

The digital transformation of industrial environments requires the ability to collect, process, and integrate data from production systems in real time. However, many manufacturing facilities operate with legacy equipment that is perfectly functional and operational but lacks native connectivity or standardized interfaces for data acquisition. This paper presents an approach to enable industrial digitalization through the implementation of a network architecture at the Operational Technology (OT) level that facilitates the collection of structured data from legacy and modern machines. The proposed solution ensures integration between production systems and supervisory platforms, supporting real-time monitoring through SCADA systems and providing relevant information for predictive maintenance strategies. The proposal is based on the implementation of a standardized and secure communication infrastructure between the shop floor and higher-level Information Technology (IT) systems, aligning with the principles of Industry 4.0. The solution has been implemented in a real industrial scenario, is fully operational and the results demonstrate significant benefits of integrating heterogeneous industrial assets into a unified data ecosystem, improving process insight, operational efficiency and supporting maintenance decision-making.

Keywords: Industry 4.0, OPC UA, Legacy Equipment Integration, Industrial Digitalization.

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1. Introduction

The ongoing digital transformation in the manufacturing sector is reshaping industrial operations, driven by advances in automation, information technologies, and cyber-physical systems integration [1]. The concept of Industry 4.0 embodies this paradigm shift, promoting connectivity between production equipment, information systems, and human operators through technologies such as the Industrial Internet of Things (IIoT), real-time data acquisition, and data analytics [2].

Despite this evolution, a significant proportion of industrial plants continue to operate with legacy production equipment, which often lack native communication capabilities or standardized interfaces for data collection and integration. These limitations difficult the ability to perform real-time process monitoring, implement predictive maintenance strategies, and fully leverage the benefits of digitalization. Consequently, integrating these heterogeneous assets into modern digital ecosystems remains a critical challenge for organizations seeking operational excellence and competitiveness [3].

One of the key enablers of this integration is the implementation of robust Operational Technology (OT)

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network infrastructures capable of collecting, structuring, and transmitting production data to supervisory platforms and higher-level Information Technology (IT) systems. In this context, interoperability standards such as OPC UA (Open Platform Communications Unified Architecture) [15] have emerged as essential tools to facilitate secure, scalable, and vendor-independent communication between different layers of industrial systems [4]. Middleware solutions, including industrial data integration platforms, further enhance this process by bridging communication gaps between legacy equipment, programmable logic controllers (PLCs), and supervisory control and data acquisition (SCADA) systems [5].

This paper presents a practical approach to support industrial digitalization by designing and implementing a data acquisition and integration solution for a manufacturing environment characterized by legacy and non-legacy equipment. The proposed architecture enables real-time data collection, structured processing, and seamless integration with supervisory systems, contributing to improved process visibility and laying the foundation for predictive maintenance practices.

The proposed solution is aligned with Industry 4.0 principles, promoting the convergence of OT and IT domains and supporting the transition to more connected, data-driven, and sustainable production systems. Furthermore, by enabling the integration of previously isolated machines, this work addresses a critical step in preparing industrial plants for future developments associated with Industry 5.0, which emphasizes human-centered, resilient, and environmentally conscious industrial operations [6].

The remainder of the paper is organized as follows: chapter 2 presents the review of the state of the art, chapter 3 the methodology followed, chapter 4 presents the experimental results and chapter 5 the conclusions.

2. State of the Art

The digital transformation of industrial environments, driven by Industry 4.0 principles, increasingly relies on the ability to integrate heterogeneous equipment and systems through robust and standardized communication and data acquisition strategies. However, many manufacturing plants still operate with legacy machines without native connectivity, limiting the potential for real-time monitoring and advanced data-driven maintenance strategies.

In this context, several studies have highlighted the need for retrofitting legacy equipment with communication modules or gateway solutions that allow the integration of these assets into modern data architectures. In [7], the authors present a Node-RED-based solution to integrate legacy systems within industrial building management environments, promoting interoperability, sustainability, and resilience in line with Industry 5.0 principles, with a focus on low-cost, user-driven digital transformation. In [8], the authors evaluate the performance of OPC UA in IIoT environments, proposing a cost-effective system architecture and testbed to assess its feasibility on resource-constrained edge devices, aiming to support protocol testing, prototyping, and education in Industry 4.0 contexts. In [9], it is proposed a big data architecture based on OPC UA to collect, harmonize, and provide industrial data enriched with metadata and semantics, enabling advanced analytics, machine learning, and repeatable simulations in Industry 4.0 environments. In [10] it was explored the role of IIoT platforms, particularly those using AWS technologies in driving digital transformation and supporting Industry 5.0 principles of human-centricity, sustainability, and resilience through practical case studies. In [11], the authors present a solution using OPC UA to enable cloud-based communication and remote operation of legacy PLCs, such as Siemens S7-1500, by bridging outdated protocols through a Raspberry Pi and TIA Portal, overcoming the limitations of manufacturer specific systems. In [12] a solution with MQTT gateways and brokers is presented to interconnect legacy industrial protocols with advanced IIoT platforms, facilitating continuous connectivity, efficient data transmission and alignment with Industry 4.0 principles, such as automation, predictive maintenance and intelligent decision making. In [13] is present a cost-effective Industry 4.0 retrofit for legacy CNC machines using gateways and sensors to enable IoT connectivity, energy monitoring, and data collection, demonstrating benefits especially for small and medium-sized enterprises. The paper presented in [14] proposes a six-layer open-source framework for the intelligent adaptation of legacy industrial machines to Industry 4.0, demonstrated on a CNC lathe, highlighting effective data acquisition, analysis, and visualization.

3. Methodology

This work was carried out at a tissue paper manufacturing facility, focused on digitizing the shop floor through data acquisition and systems integration to support predictive maintenance. The main objective was to interconnect all plant machines to a centralized SCADA system, enabling real-time monitoring and operational data collection. The machine fleet consists of a heterogeneous set of PLCs, with some legacy devices lacking native support for the OPC UA protocol and supporting only Siemens S7 communication. In order to integrate the PLC into the plant network and enable IP-based connectivity, Profinet/Ethernet communication modules were added. These modules allow the PLC to be addressed within the network infrastructure. Despite this integration, all communication with the PLC continues to rely on the S7 protocol. For the newer PLCs equipped with native OPC UA server functionality, a straightforward configuration was performed to expose data through OPC UA. A middleware layer was established using the *vNode* [16] platform, which served as a communication broker and data aggregator, ensuring interoperability between multiple PLCs and higher-level software. *vNode* was selected for its native support for a wide range of industrial protocols, lightweight implementation, and flexible integration capabilities, without the need for additional drivers or connection licensing. Solutions based on Kepware [17], Ignition [18], or other technologies involve higher licensing costs and resource overhead. *vNode* is a simplified and scalable alternative, especially suited for edge-level interoperability in distributed architectures.

The communication infrastructure was enhanced with the deployment of a fiber optic ring network throughout the factory floor, connecting all PLCs to ensure high-speed data transfer. The industrial IP network was configured over this fiber optic backbone to support standardized communication protocols and enable scalable system expansion. The vNode middleware was integrated with *Honeywell's Uniformance Suite* to manage acquired data and visualize it through dashboards. This integration allowed operators and maintenance personnel to monitor machine status, analyze trends, and implement predictive maintenance strategies. This implementation unified legacy and modern equipment under a single architecture aligned with Industry 4.0 principles. It optimized data flow from the factory floor to the supervisory layer, supporting more informed decision-making.

Figure 1 illustrates the layout of the implemented shop floor infrastructure. The optical fiber ring interconnects all machines on the shop floor, ensuring high-speed communications. The production environment includes machines with different topologies, some supporting communication protocols such as OPC UA and Siemens S7, and others without native communication interfaces. All machines were integrated using vNode middleware, which serves as a central hub for data unification. From vNode, data is made available to supervisory systems, including SCADA, ERP, and MES platforms, as well as factory databases and cloud-based services.

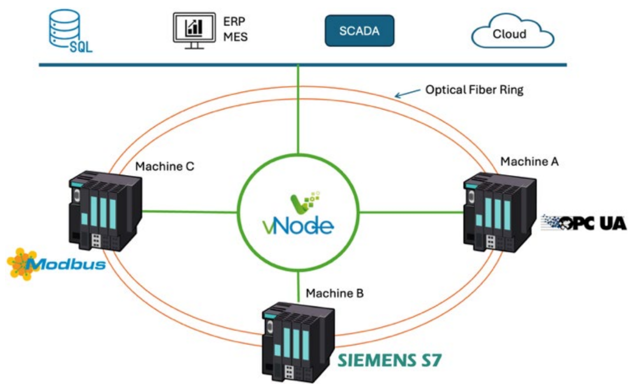

Figure 1. System Architecture Layout.

4. Experimental Results

The proposed architecture was implemented on the shop floor of the Transformation area of the company, aiming to interconnect modern and legacy machines through a unified optical fiber ring. The *vNode* platform played a central role in enabling the integration of various devices, standardizing data collection, and exporting the acquired information to monitoring and analysis systems, specifically *Honeywell Uniformance*.

Approximately 2,000 meters of optical fiber cable and 1,500 meters of UTP cable were installed, and approximately 70 PLCs were prepared for integration into the OT network. Several electrical panels were installed to support the communication backbone, as illustrated in Figure 2, which shows one of the OT network cabinets connected to the Makeup Tank equipment.

The *vNode* platform proved to be an effective middleware solution, enabling integration with various Siemens PLC models using the S7 and OPC UA protocols. Communication with the pilot machines, namely the Paper Rewinder (shown in Figure 3) and the Makeup Tank, was established without data loss, demonstrating the system's stability and robustness.

Figure 4 shows a *Uniformance* system dashboard displaying the rewinder speed in real time. This visualization confirms the system's ability to collect and deliver real-time data to monitoring platforms, enabling faster and more accurate operational decision-making.

Regarding data acquisition latency, a minimum latency of *500 ms* was achieved during testing. To ensure the stability and robustness of the entire system, critical variables are acquired every *1 s* and non-critical variables every *5 s*.

Although implementation is recent and operational data is still being collected, initial observations indicate greater visibility into equipment status and a reduction in manual inspection routines. For example, during the testing phase, one episode demonstrated the benefits of the implemented system through early detection of a fault in a replacement tank, located in an area with low operational visibility. Without the monitoring solution, identifying the problem would have taken considerably longer. The system detected a gradual decrease in temperature over several days, deviating from the expected setpoint, which ultimately revealed a failure in the steam valve opening. This case highlights the value of continuous, automated monitoring, particularly for critical equipment located in less supervised areas.

Figure 2. OT network electrical panels, housing the industrial switches and optical fiber ring terminations that support the plant's communication infrastructure.

Figure 3. Paper Rewinder Machine.

Figure 4. Dashboard view in *Honeywell Uniformance* showing the real-time speed graph of the rewinder machine.

5. Conclusions

This work presents a practical case study of the implementation of a data acquisition and processing solution based on the OT network architecture and the *vNode* platform. In a pilot phase, the infrastructure was tested and validated in a real operational environment, demonstrating reliable communication with existing PLCs and stable real-time data acquisition. This foundation allows the system to be scalable to additional production lines. In addition to the immediate technical and operational benefits, this work is important for the company in terms of aligning itself with the principles of Industry 4.0. Structured data collection and integration with analytical platforms enable more proactive and data-driven management, with a focus on operational efficiency. In other hand, the solution marks a significant step towards Industry 5.0, emphasizing human-machine collaboration, sustainability and well-being in the workplace.

As future work aims to integrate all factory machines into the proposed architecture and implement automatic anomaly detection solutions at the supervisory system level. Data analysis will be used to identify trends and support predictive maintenance solutions.

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References

[1] Xu, L. D., Xu, E. L., & Li, L. (2018). Industry 4.0: state of the art and future trends. *International Journal of Production Research*, *56*(8), 2941–2962. https://doi.org/10.1080/00207543.2018.1444806.

[2] Liao, Y., Deschamps, F., Loures, E. de F. R., & Ramos, L. F. P. (2017). Past, present and future of Industry 4.0 - a systematic literature review and research agenda proposal. *International Journal of Production Research*, *55*(12), 3609–3629. https://doi.org/10.1080/00207543.2017.1308576.

[3] Kang, H.S., Lee, J.Y., Choi, S. *et al.* (2016). Smart manufacturing: Past research, present findings, and future directions. *Int. J. of Precis. Eng. and Manuf.-Green Tech.* **3**, 111–128. https://doi.org/10.1007/s40684-016-0015-5.

[4] Mahnke W, Leitner SH, Damm M. OPC Unified Architecture. Berlin: Springer; 2009. 332 p.

[5] Horak, T., Strelec, P., Kebisek, M., Tanuska, P., & Vaclavova, A. (2022). Data Integration from Heterogeneous Control Levels for the Purposes of Analysis within Industry 4.0 Concept. *Sensors*, *22*(24), 9860. https://doi.org/10.3390/s22249860.

[6] European Commission (2021). Industry 5.0: Towards a sustainable, human-centric and resilient European industry. Luxembourg: Publications Office of the European Union.

[7] Korodi, A., Nițulescu, I.-V., Fülöp, A.-A., Vesa, V.-C., Demian, P., Braneci, R.-A., & Popescu, D. (2024). Integration of Legacy Industrial Equipment in a Building-

Management System Industry 5.0 Scenario. *Electronics*, *13*(16), 3229. https://doi.org/10.3390/electronics13163229.

[8] Ladegourdie, M., & Kua, J. (2022). Performance Analysis of OPC UA for Industrial Interoperability towards Industry 4.0. *IoT*, *3*(4), 507-525. https://doi.org/10.3390/iot3040027.

[9] Hirsch, E., Hoher, S., & Huber, S. (2023). An OPC UA-based industrial Big Data architecture. *arXiv (Cornell University)*. https://doi.org/10.48550/arxiv.2306.01418.

[10] Torres, P. M. B., Spencer, G., Lopes, P., & Santos, F. (2024). Industrial IoT platforms enabling industry 4.0 digitization towards industry 5.0. In *Lecture notes in mechanical engineering* (pp. 1–12). https://doi.org/10.1007/978-3-031-61575-7_1.

[11] R. H, S. J. Fusic, J. Cornelius K S R, S. M and A. M, (2023). Case study on Integrating Legacy Devices in Industry 4.0 framework using OPC UA, *2023 International Conference on Energy, Materials and Communication Engineering (ICEMCE)*, Madurai, India, pp. 1-6, doi:10.1109/ICEMCE57940.2023.10434133.

[12] S. Yolov, G. Hristov and P. Zahariev (2025), Development and Integration of an Industrial Automation System based on the MQTT Protocol, *2025 Joint International Conference on Digital Arts, Media and Technology with ECTI Northern Section Conference on Electrical, Electronics, Computer and Telecommunications Engineering (ECTI DAMT & NCON)*, Nan, Thailand, pp. 79-84, doi:10.1109/ECTIDAMTNCON64748.2025.10962086.

[13] A. Vicentin and F. Lima (2024), Retrofitting Legacy CNC Machines with a Focus on Energy Consumption," *2024 International Conference on Sustainable Technology and Engineering (i-COSTE)*, Perth, Australia, pp. 1-6, doi: 10.1109/i-COSTE63786.2024.11025111.

[14] Patel, D., & Muthuswamy, S. (2024). An open framework for smart retrofitting of legacy industrial machines towards industry 4.0. *TENCON 2021 - 2021 IEEE Region 10 Conference (TENCON)*, 971–974. https://doi.org/10.1109/tencon61640.2024.10902873.

[15] OPC UA, OPC Foundation, https://opcfoundation.org/, accessed on July 2025.

[16] vNODE, https://vnodeautomation.com/, accessed on July 2025.

[17] Kepware, https://www.ptc.com/en/products/kepware, accessed on July 2025.

[18] Ignition, https://inductiveautomation.com/ignition/, accessed on July 2025.