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Design and Implementation of a Machine Feedback System with Dual Digital Twins for Industrial Safety Applications

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The industry 4.0 paradigm ensures that modern machinery is networked and equipped with sensors capable of sharing operational states with the digital factory. This work pursues two main goals: assessing the system's capability to manage hazard notifications within defined uncertainty bounds and designing a prototype of an "intelligent" machine system. Activities were divided into two main areas. First, a communication system was developed and implemented to enable the real machine to exchange operational data with a Python-based backend server. The Data Collector Manager was configured to define the machine network, acquisition parameters, and communication protocols, ensuring reliable machine-server interactions with metrological traceability. Data were acquired via a real CN industrial network protocol, allowing efficient transmission of operational information with adequate temporal resolution and management of downtime and maintenance events. Second, a Python-based digital twins were deployed on Raspberry Pi devices to emulate machine-server communication. The digital twin includes an interface allowing users to simulate machine states, alarms, and maintenance actions, transmitted to the same backend server used by the real machine. This guarantees synchronized and coherent interaction between physical and virtual systems, supported by precise time stamping. A unified dashboard, hosted on an external PC, enables real-time monitoring with minimal latency of machine status, diagnostics, and alarms from both real and virtual systems. The system successfully identified safety violations, such as spindle guard tampering, through predefined alarm thresholds with high sensitivity and specificity, ensuring prompt hazard detection. Experimental validation under standardized protocols confirmed continuous, synchronized data flow with no packet loss and stable updates under variable load conditions, within acceptable measurement error limits. The proposed architecture demonstrates robustness and reliability for data acquisition, monitoring, and decision support, effectively enhancing safety and operational efficiency in industrial environments.

Keywords: *Industrial Safety Monitoring, Digital Twin Communication, Machine-Server Data Acquisition.*

1. Introduction

The integration of cyber-physical systems in modern industrial environments has significantly improved worker safety and operational efficiency (Lee et al., 2015; Tao et al., 2018). Nevertheless, machinery-related accidents caused by malfunctions, unauthorized modifications, and insufficient hazard communication remain a major concern. European safety regulations, such as the Machinery Directive 2006/42/EC (European Parliament and Council, 2006), require industrial equipment to implement effective risk reduction measures and clear hazard communication. Traditional monitoring systems, typically based on centralized SCADA architectures (Stouffer et al., 2011), collect data from PLCs but often lack the flexibility and intelligence needed for proactive safety management. In addition, testing new safety strategies directly on operating machinery is risky and may disrupt production. Digital twin technology addresses these limitations by enabling virtual representations of physical assets, allowing safe experimentation, predictive maintenance, and improved situational awareness. However, industrial safety monitoring still faces challenges, including limited real-time feedback, delayed event communication, difficulties in integrating heterogeneous devices (Sisinni et al., 2018), and the need for metrological traceability through accurate data integrity and time synchronization. Furthermore, unreliable hazard detection, due to false alarms or missed events, can undermine operator trust (Villani et al., 2018). This work proposes an intelligent machine feedback system based on dual digital twins to support reliable and real-time safety monitoring in industrial environments. The approach focuses on ensuring data integrity, temporal synchronization, and robust communication between physical machines and their virtual counterparts in safety-critical scenarios. A modular communication architecture is designed to enable metrologically traceable data exchange between industrial machines and a centralized monitoring platform. Digital twin replicas accurately represent machine behavior, operational states, and safety events in a controlled virtual environment (Negri et al., 2017; Kritzinger et al., 2018; Tao et al., 2019). The system is validated in terms of response time, uncertainty bounds, synchronization, and data transmission reliability under variable operating conditions. The main contributions include a modular architecture integrating physical machines, dual digital twins, and a unified monitoring dashboard using standardized communication protocols such as HTTP POST (Profanter et al., 2019) and the proprietary EPS protocol. Experimental results show zero packet loss and millisecond-level latency, as well as effective detection of safety-critical events, including spindle guard tampering and connector disconnection. The framework also enables safe testing and validation of safety procedures without interfering with production. From a technological perspective, the work builds on recent advances in digital twin and industrial communication technologies. Data acquisition from CNC machines is performed via the EPS protocol, which supports configurable triggers and structured data formats, while HTTP-based communication ensures interoperability with modern monitoring platforms (Profanter et al., 2019). Safety monitoring is implemented through threshold-based detection using time-stamped data, enabling accurate identification and correlation of safety-critical events across distributed industrial systems. While digital twin technology has been extensively explored for predictive maintenance and process optimization, its application to real-time industrial safety monitoring remains limited. Existing implementations typically deploy single digital twin instances, which impose significant constraints: (i) testing safety procedures on the virtual replica disrupts monitoring of the physical asset, (ii) parallel evaluation of multiple fault scenarios is not feasible, (iii) stress-testing the backend infrastructure under concurrent multi-machine alarms cannot be performed without production risks, and (iv) validation campaigns must be conducted sequentially rather than in parallel. Furthermore, acoustic monitoring (critical for comprehensive safety assessment) is rarely integrated in digital twin frameworks with quantitative validation. This work addresses these limitations through a dual digital twin architecture specifically designed for industrial safety applications. Unlike single-instance deployments, the dual architecture separates the monitoring role (Twin A mirrors the physical machine) from the testing role (Twin B serves as a safe experimental sandbox), thereby enabling concurrent production oversight and fault-injection campaigns.

2. System Architecture

The system integrates a lathe with CNC Z32 industrial control and dual Raspberry Pi-based digital twins and a Python backend server with web dashboard (figure 1). This architecture enables simultaneous monitoring of physical and simulated operations.

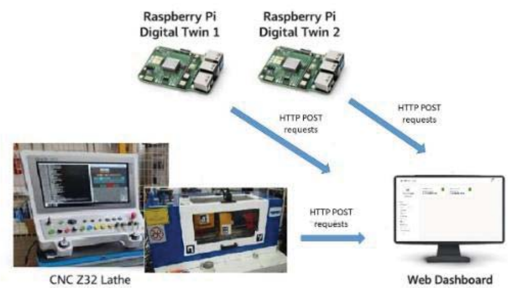

Fig. 1. Dual Raspberry Pi-based digital twins and a Python backend server with web dashboard

The key requirements are: no data loss under normal and variable load conditions; precise time stamping for event correlation across physical/virtual systems; modular design supporting additional machines; rapid hazard detection with minimal latency; verifiable data integrity and temporal accuracy. The CNC Z32 lathe is equipped with a modified PLC interfaced with the monitoring infrastructure through D.Electron's Data Collector Manager (D. Electron, 2019), which acts as the middleware between machine control and the supervisory system. DCM operates based on two configuration files that define both the communication architecture and the data acquisition strategy. The *DCM.ini* file specifies the overall system configuration, including the machine network structure, connection parameters such as IP address, communication port, protocol type (EPS – Easy Protocol Server), and the path to the associated profile file, as well as the configuration of an HTTP printer using the POST method for data transmission to the backend server, with optional proxy settings for network routing. The *dcmprofile.ini* file defines the complete logic for data acquisition and transmission. It specifies the PLC variables to be acquired through EPS commands, including machine states and sensor values, alarm messages and codes, and program execution information such as cycle times and part counts. The file also defines the conditions under which data acquisition is triggered, including event-based triggers activated by specific PLC variable transitions, alarm-based triggers activated upon any alarm occurrence, and polling mechanisms for periodic data collection at configurable intervals (roughly 1 to 5 seconds depending on different message types). The structure of transmitted data is defined through HTTP POST templates comprising a machine identifier, data category, numeric or state value, textual description, and a timestamp. Finally, output definitions link triggers, templates, and communication endpoints to establish complete and coherent data flows toward the backend system. This configuration enables asynchronous transmission of critical machine information (figure 2), including operational state changes, safety-related events such as spindle guard opening or emergency stops, maintenance notifications, and production metrics. Data buffering mechanisms ensure resilience against temporary communication interruptions, while priority handling guarantees that safety-critical information is transmitted with precedence, supporting reliable and timely industrial safety monitoring.

Fig. 2. Data transmission layout between real machine and server: I) lathe console + DCM, II) HTTP POST server, III) Modem for lathe and server connection

Two Raspberry Pi 5 devices run Python and Qt-based graphical clients (Qt Company, 2024) that replicate the functionality of the Data Collector Manager without requiring physical hardware. These digital twins (figures 3, 4) simulate all machine states, including operational modes, alarms, and maintenance events, while allowing users to trigger events interactively via the graphical interface. They maintain identical data formats and communication protocols as the physical machines and operate independently, enabling simultaneous testing of multiple scenarios. In addition to state and alarm simulation, the digital twin supports acoustic emulation of machine operation. Machine noise is reproduced through an external audio output using pre-recorded audio signals acquired on real industrial machines and managed by Python-based processing scripts. This functionality extends the digital twin beyond purely logical state replication, enabling realistic representation of noise-related operating conditions.

Fig. 3. 1) Data transmission layout; 2) Digital twin of machine on Raspberry Pi

Fig. 4. Raspberry Pi–based digital twin prototype featuring a graphical user interface for interactive simulation of machine operational states, alarms, and maintenance events. An external audio speaker reproduces machine noise from pre-recorded audio signals acquired on real industrial machines.

A single web-based dashboard (figure 5) hosted on an external PC provides both data acquisition and monitoring capabilities. It manages communications with the digital twins, synchronizes timestamps, evaluates alarms against predefined safety thresholds, and stores historical data. The dashboard presents real-time operational states, active alarms with severity and timestamps, and historical trends, while also supporting automated safety violation notifications and configurable parameters. By integrating all backend functions within a single interface, the system offers a streamlined and user-friendly platform for comprehensive monitoring and scenario testing.

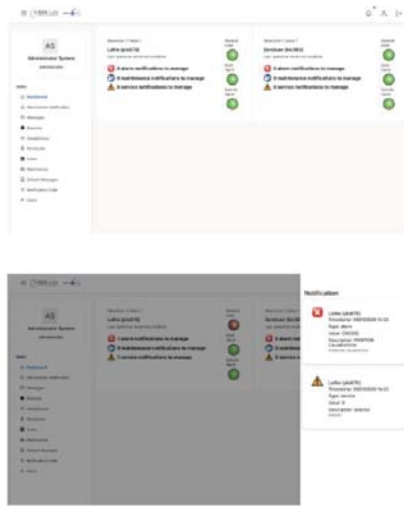

Fig. 5. Web-based dashboard hosted on an external PC, integrating data acquisition, digital twin communication, and real-time monitoring of machine operational states

3. Implementation

All components of the system operate with synchronized clocks using the Network Time Protocol (Mills et al., 2010), ensuring temporal coherence across distributed devices. Previous studies on state-space modeling for arrival time simulations highlight methodologies to characterize software-based measurement systems, providing guidance for implementing accurate and reliable digital twin architectures (Tocci et al., 2023). Multi-level timestamping is applied at the stages of data acquisition, transmission, and reception, allowing for accurate latency evaluation, event correlation, and identification of potential processing or communication bottlenecks. Data integrity is ensured through validation of message structure, verification of physically plausible value ranges, sequence numbering to detect missing or duplicated data packets, and checksum-based error detection during transmission. The overall measurement uncertainty is influenced by intrinsic sensor accuracy and calibration, temporal quantization effects due to finite sampling rates, variability in network latency, and processing delays introduced by signal processing. The digital twin interface (figure 6), developed using Qt Creator, provides comprehensive control over the simulated machine behavior and operating conditions. It enables the simulation of machine states, including operational modes, motion conditions, and production cycles, as well as the generation of alarms ranging from standard machine notifications to safety-critical events such as guard tampering or emergency stops, with configurable severity levels and support for sequential triggering of compound scenarios. The interface also manages maintenance-related events, allowing both scheduled and unscheduled triggers with countdown timers and completion confirmation. Data transmission to the backend can be manually initiated, automatically performed at periodic intervals, or executed in burst mode for stress-testing purposes. Visual feedback within the interface confirms successful data transmission and backend acknowledgment, while error conditions are clearly highlighted to support rapid diagnosis. In order to enhance the realism of the digital twin and enable acoustic-related safety testing, industrial recorded machine noise was reproduced audio data were recorded in WAV format through a dedicated Python-based acquisition script connected to a microphone, which performed real-time computation of the equivalent continuous sound pressure level (Leq) during signal capture. The same audio signals were subsequently analyzed offline to compute Leq values from the corresponding WAV files acquired. The real-time and offline Leq results showed excellent agreement, confirming the consistency and reliability of the acquisition and processing pipeline. This approach allows the digital twin to reproduce realistic acoustic operating conditions while ensuring quantitative consistency between simulated and measured sound exposure metrics. The comparison between real-time and offline equivalent continuous sound pressure level (Leq) values shows an error below 0.5 dB across all tested industrial machines.

Fig. 6. Digital twin interface developed using Qt-Creator

Communication between machines and the dashboard is based on HTTP POST requests (figure 7), selected for their standardization, implicit acknowledgment mechanisms, straightforward retry logic, and compatibility with common security solutions such as HTTPS and token-based authentication. On the backend, incoming data are handled through a structured processing pipeline that includes request validation, timestamp handling, database insertion, alarm condition evaluation, and response generation, ensuring reliable and traceable data exchange across the system.

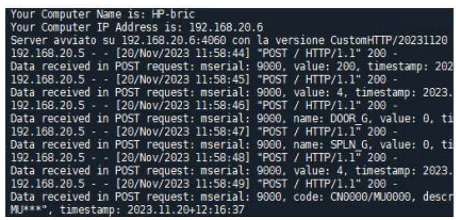

Fig. 7. Example of transmitted strings

4. Experimental Validation

The experimental validation was designed to assess communication reliability, temporal accuracy, hazard detection capability, and overall system synchronization. Tests were conducted in a laboratory environment configured to replicate an industrial network topology, including representative traffic loads and variable operating conditions. Instrumentation included server-side logging with microsecond-resolution timestamps, client-side transmission logs, network packet capture for traffic analysis, and response time measurements collected from the monitoring dashboard. Communication performance was evaluated under multiple transmission scenarios, including normal operation, sustained high-frequency updates, burst transmissions, simulated network congestion, and WiFi connectivity. No packet loss was observed throughout the extended validation period, confirming reliable data delivery across all tested conditions. Latency measurements showed minimal variance, indicating stable system behavior, with digital twin instances exhibiting slightly lower latency compared to physical machines due to the absence of PLC-related processing delays. Time-stamped data originating from all system sources were consistently aligned, enabling accurate reconstruction of event timelines and parallel monitoring of multiple machines. The system demonstrated robust safety event detection capabilities during validation tests. Spindle guard tampering events (figure 8) were detected with full sensitivity and no false positives over extended monitoring periods, with alarm thresholds effectively distinguishing genuine safety violations from normal operational variations. Connector disconnection events were identified immediately, triggering distinct alarm codes and automatic incident logging to support maintenance activities. In multi-event scenarios involving concurrent alarms from multiple machines, the system correctly prioritized critical events and provided clear sequential visualization on the dashboard, ensuring effective situational awareness.

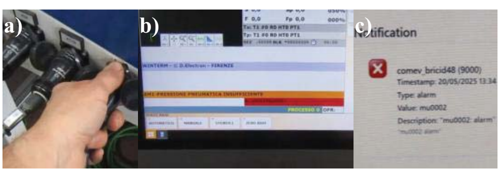

Fig. 8. The operator disconnects the spindle guard safety connector between the lathe and the CNC console (a) , triggering a PLC alarm (b) that, through a specific manufacturer code, is also published on the frontend dashboard for real-time monitoring (c).

Under stress-testing conditions with increasing transmission rates, the system maintained reliable operation without packet loss up to the maximum tested load. Although latency increased modestly under peak conditions, it remained within acceptable limits, and the backend preserved real-time performance without queue accumulation. Long-duration stability tests confirmed continuous operation without server crashes or client disconnections, showing no performance degradation over time and successful automatic recovery from transient network interruptions. The system achieved a sensitivity of 1.0 and a specificity of 1.0 across all monitored event types, with no missed detections and no false positives throughout the entire validation campaign. End-to-end latency remained consistently low under baseline conditions and within acceptable bounds even during burst transmission scenarios. Overall, these results confirm that the proposed architecture meets the core requirements of a supervisory safety monitoring system: deterministic event delivery, prompt hazard detection, and stable long-duration operation.

5. Discussion

The proposed architecture, based on HTTP POST with acknowledgment and retry mechanisms, achieves reliable and deterministic behavior suitable for safety-critical industrial applications. The absence of packet loss and bounded, predictable latencies ensure timely hazard notification. Compared to traditional centralized SCADA solutions, the system offers enhanced responsiveness and flexibility while preserving traceability and data integrity. The system demonstrates high effectiveness in detecting safety-critical events, achieving full detection sensitivity with no false positives. The threshold-based alarm strategy provides robust safety monitoring without alarm fatigue. The architecture provides added value to risk mitigation: machine-level sensors and PLC logic ensure immediate local responses, while digital twin and backend layers provide supervisory situational awareness. This layered approach supports both real-time hazard notification and post-event analysis for continuous safety improvement. The adoption of a dual digital twin configuration represents a key contribution of this work. The availability of two independent yet synchronized digital twins enables parallel testing, fault injection, and comparative evaluation of safety strategies without interfering with production activities. This capability allows developers and safety engineers to validate alarm logic, communication behavior, and system responses under multiple concurrent scenarios, including rare or hazardous conditions that would be impractical or unsafe to reproduce on physical machinery. Compared to single digital twin implementations (Jones et al., 2020; Semeraro et al., 2021), the dual approach increases experimental flexibility and supports more comprehensive validation campaigns, including stress-testing of the backend infrastructure and evaluation of event prioritization mechanisms under multi-machine conditions. As a result, the system not only supports operational monitoring but also functions as a virtual testbed for safety system development and commissioning. Standardized HTTP-based communication and modular architecture facilitate scalability and straightforward extension to additional machines without substantial modifications. The decoupling between data acquisition, digital twin simulation, and backend processing enables seamless integration with higher-level enterprise systems such as maintenance management and production planning platforms, positioning the framework as a practical solution for broader industrial digitalization initiatives. Despite the demonstrated robustness, the system remains partially dependent on network availability, which may represent a limitation in highly constrained or degraded communication environments. This issue can be mitigated through local buffering strategies, redundant communication paths, and the integration of localized safety logic capable of operating autonomously during network outages. Alarm configuration currently relies on manually defined thresholds based on engineering expertise. Future developments will investigate the integration of data-driven and machine learning techniques (Carvalho et al., 2019; Paolucci et al., 2025) to automatically adapt alarm thresholds based on historical operational data, potentially improving detection robustness under evolving operating conditions. Additional research directions include enhancing digital twin fidelity through physics-based modeling, integrating additional sensing modalities such as vibration, thermal, and acoustic data, and exploring autonomous response mechanisms to further reduce operator workload. Large-scale, multi-site deployments will also be considered to assess system performance and reliability in more complex industrial scenarios. The proposed system functions as a supervisory monitoring layer and does not replace the machine's certified safety functions (PLC interlocks, safety relays). It therefore operates outside the scope of IEC 62061/ISO 13849 safety integrity level requirements but complements them by providing real-time situational awareness and post-event traceability.

Conclusions

This work presented the design, implementation, and experimental validation of an intelligent machine feedback system integrating dual digital twins for industrial safety applications. The proposed architecture successfully enables real-time monitoring and robust hazard detection for CNC machines, ensuring data integrity, temporal synchronization, and metrological traceability. The dual digital twin approach proved particularly effective in providing parallel testing and scenario simulation without interfering with production, allowing safe evaluation of alarm logic, fault injection, and system behavior under complex or hazardous conditions. Experimental results demonstrated the system's high reliability, with zero packet loss, minimal latency, and consistent performance across both physical and virtual systems under variable load conditions. Safety-critical events, including spindle guard tampering and connector disconnections, were detected with full sensitivity and no false positives, validating the effectiveness of the threshold-based alarm strategy. The unified dashboard provided comprehensive situational awareness, supporting both real-time hazard notification and post-event analysis, thus enhancing operator safety and enabling continuous improvement in industrial safety management. The proposed framework also exhibits significant scalability and interoperability potential, allowing integration with additional machines, heterogeneous devices, and enterprise-level systems. While current limitations include dependency on network availability and manually configured alarm thresholds, future work will explore data-driven threshold adaptation, increased digital twin fidelity through physics-based modeling, integration of additional sensing modalities, and autonomous response mechanisms. Large-scale deployment and multi-site validation are also envisioned to further assess the system's robustness and applicability in diverse industrial scenarios. Overall, this study demonstrates that combining dual digital twins with a modular, metrologically traceable communication architecture can significantly enhance industrial safety monitoring, providing a reliable platform for both operational supervision and virtual safety testing.

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