Proceedings in Manufacturing Systems, Volume 20, Issue 4, 2025, pp. 145-151 ISSN 2067-9238

EPICS-BASED INTEGRATION OF PLC SAFETY SYSTEMS FOR A DIGITAL TWIN IMPLEMENTATION

Aurelian IONESCU[1,*], Robert PATRASCOIU[2], Alexandra CANA[3], Andrei IANCU[4]

[1)] PhD Student, Eng, Doctoral School of Industrial Engineering and Robotics, National University of Science and Technology POLITEHNICA Bucharest, Romania
[2)] PhD Student, Eng, Gamma System Dep, ELI-NP, Magurele, Romania
[3)] Student, Eng, Gamma System Dep, ELI-NP, Magurele, Romania
[4)] Student, Eng, Gamma System Dep, ELI-NP, Magurele, Romania

Abstract: *This paper presents a compact Digital Twin architecture for PLC-based safety systems, implemented at the ELI-NP LINAC Gamma Beam System (GBS). The Machine Protection System (MPS) and Personnel Protection System (PPS) are implemented on Siemens S7-1500 PLCs and must ensure high reliability, short reaction times and full traceability of safety events. To integrate these safety systems into the facility-wide EPICS environment, a layered data chain is implemented: Siemens S7-1500 → s7nod driver → EPICS IOC → EPICS Archiver Appliance → Grafana. The PLC executes the safety logic and acquires process signals (vacuum, cooling temperature and flow, access status), while EPICS exposes these internal variables as Process Variables (PVs) for monitoring, archiving and visualisation. The paper summarises the configuration of the ISO-on-TCP link between PLC and EPICS, mapping of PLC memory into PV records, and use of Archiver Appliance and Grafana for real-time and historical analysis. A Hardware-in-the-Loop (HIL) case study on a Mydax precision chiller shows how the Digital Twin is used to validate the cooling subsystem behaviour and safety reactions. The proposed architecture provides a compact, extensible solution for Digital Twin-based monitoring and safety system testing..*

Key words: *Digital Twin, EPICS, PLC Siemens S7-1500, safety interlocks, Archiver Appliance, Grafana, Hardware-in-the-Loop.*

1. INTRODUCTION

The operation of high-power accelerator facilities requires robust safety systems, capable of detecting abnormal conditions and deterministically triggering protective actions. Thus, modern facilities increasingly rely on digital twin concepts to support commissioning, diagnostics, risk assessment and operator training.

At ELI-NP the Gamma Beam System (GBS) LINAC is protected by two PLC-based safety subsystems: the Machine Protection System (MPS), which safeguards equipment, and the Personnel Protection System (PPS), which safeguards personnel by enforcing access control and emergency procedures. In parallel, the facility uses the EPICS (Experimental Physics and Industrial Control System) framework as the main control and integration platform for beamline and experimental subsystems.

In this context, a key challenge is the integration of PLC-based safety systems into the EPICS environment without compromising their integrity. The digital twin must be able to "see" the safety logic, record its reactions, and, in controlled Hardware-in-the-Loop (HIL) scenarios, stimulate the system using realistic conditions.

The problem addressed in this paper is how to create a simple but robust integration chain that connects Siemens S7-1500 safety PLCs with EPICS, data archiving and visualisation tools, in order to support a Digital Twin of the safety functions. The application field is the ELI-NP GBS cooling and protection infrastructure, with focus on a precision chiller used as critical MPS equipment.

The authors' concept is to treat EPICS as an integration layer between the industrial automation level (PLC) and the Digital Twin analysis level (Archiver, Grafana, GUIs). Rather than re-implementing safety logic, the Digital Twin uses the PLC's native logic and observes it through EPICS PVs.

The original contribution of the work can be summarised as:

- a compact, implementable architecture: PLC → s7nod → EPICS IOC → Archiver → Grafana;
- a documented method for mapping S7-1500 memory into EPICS PVs for safety monitoring;
- a HIL case study on a Mydax precision chiller, illustrating Digital Twin-based validation of a real subsystem.

2. PROBLEM DESCRIPTION AND APPLICATION FIELD

2.1. Safety systems in the GBS facility

The Gamma Beam System Linear Accelerator at Extreme Light Infrastructure – Nuclear Physics in Magurele, Romania combines high-brightness electron

* Corresponding author: Splaiul Independentei 313, Sector 6, 060042, Bucharest, Romania
Tel.: +0040725376516
E-mail address: *aurelian.ionescu85@stud.fiir.upb.ro* (A. Ionescu)

beam, Radio Frequencies systems and complex experimental areas [1].

The MPS and PPS are implemented on Siemens S7-1500 PLCs. The MPS monitors technical parameters (cooling water, vacuum, radio frequencies status), while the PPS monitors access doors, key panels and area status. Both subsystems must operate autonomously, with deterministic response times and certified reliability.

From a Digital Twin perspective, two needs arise:

- to observe MPS/PPS decisions and their correlation with process variables.
- to inject controlled test stimuli (in HIL mode) in order to validate logic and thresholds before applying changes to the real machine.

2.2. Requirements for the Digital Twin integration.

The integration of PLC safety systems into a Digital Twin must satisfy several constraints:

- *Non-intrusiveness*: the safety logic must remain inside the PLC; external tools should not bypass or alter it.
- *Real-time visibility*: critical PLC variables must be available as EPICS PVs with suitable refresh times.
- *Traceability*: events and safety-relevant parameters must be archived for post-mortem analysis and optimization.
- *Scalability*: the architecture must allow future extension to additional subsystems (RF, vacuum, access control).
- *Support for HIL*: the chain must allow safe testing with the real PLC in the loop.

3. METHODS: PLC-EPICS-ARCHIVER-GRAFANA-CHAIN

3.1. System architecture

The proposed architecture is organized into five layers:

- *Layer* 1 – *PLC Siemens S*7-1500: executes MPS/PPS logic and acquires signals from sensors and equipment (e.g. cooling loops, vacuum gauges, access switches).
- *Layer* 2 – *s7nod device support*: an EPICS driver that connects to the PLC via ISO-on-TCP (S7 protocol, port 102) and maps PLC memory areas (inputs, outputs, data blocks) to EPICS PVs.
- *Layer* 3 – *EPICS IOC*: runs on a Linux server, hosts EPICS records and publishes PVs to client application.
- *Layer* 4 – *EPICS Archiver Appliance*: stores PV time series with configurable sampling rates and retention policies.
- *Layer* 5 – *Grafana*: visualisation and analysis layer that queries the Archiver and displays dashboards for operators and engineers.

In normal operation, the PLC remains the master of safety actions, while EPICS, Archiver and Grafana provide observation, analysis and reporting.

3.2. PLC-EPICS integration using s7nod

Communication between the S7-1500 and EPICS is based on the native Siemens ISO-on-TCP protocol over Ethernet. In the TIA Portal project, access level is set to *Full* and GET/PUT communication is enabled for the relevant data blocks by disabling “optimized block access”. This allows external clients to address the PLC memory directly.

On the EPICS side, the s7nod device support is used in the IOC. The connection is declared in the IOC startup script via a command of the form:

```
s7nodaveConfigureIsoTcpPort("S7_1500",
"192.168.111.120", 0, 0, 0)
```

where "S7_1500" is a logical PLC name, and the rack/slot parameters identify the CPU. Once this logical connection exists, EPICS records can refer to PLC memory using addresses such as @S7_1500 IB0 (inputs), @S7_1500 QB0 (outputs) or @S7_1500 DB1.DBW0 (data blocks).

Process variables are defined by standard EPICS records (bi, bo, mbbi, ai, ao etc.). For example, an analogue input reading a pressure value from a data block may be defined as:

```
record(ai, "PLC:Pressure") {
  field(DTYP, "s7nodave")
  field(INP,  "@S7_1500 DB1.DBW0")
  field(EGU,  "bar")
}
```

To improve performance, related PVs (e.g. cooling temperatures and flows) are grouped into poll groups with common scan periods (e.g. 1 s), so that multiple variables are read in a single block transfer.

Write access from EPICS to the PLC is enabled only for dedicated command bits or test flags. Safety logic in the PLC remains authoritative; HIL tests are performed with appropriate isolation of field devices [2].

3.3. Data archiving with EPICS Archiver Appliance

The EPICS Archiver Appliance is used as a time-series database for safety-relevant PVs. Selected PVs

(e.g. *PLC:Chiller_Temp_L1*, *PLC:Chiller_Flow_L2*, *PLC:MPS_Status*)

are added to the archiver with sampling rates typically around 1 Hz.

The Archiver organises data into short-term, medium-term and long-term stores, allowing fast access to recent data and efficient compression for historical records. This provides the Digital Twin with a persistent memory of system behaviour, essential for:

- analysing interlock events;
- validating modifications to safety logic;
- supporting future predictive algorithms.

3.4. Visualisation and analysis with Grafana

Grafana is configured with a data source that queries the Archiver’s retrieval interface. Dashboards are built to display:

- real-time and historical plots of cooling temperatures, flows and pressures;
- status indicators for MPS/PPS;
- threshold bands and alarm colours;

- trend lines or polynomial regression fits for selected signals.

For the cooling system, for example, one dashboard can show the three chiller loops on the same graph, with set-points and alarm limits overlaid. In addition, alert rules can be defined in Grafana to issue notifications when average values or gradients exceed predefined limits.

In this way, Grafana acts as the main visualization layer of the Digital Twin, providing a unified view of PLC safety variables and their evolution in time.

4. RESULTS: HIL CASE STUDY – MYDAX PRECISION CHILLER

4.1. Integration and test setup

The integration was performed through the following main steps:

- Identification of the temperature, flow and pressure sensor addresses of the Mydax chiller and connection of these signals to the analog and digital I/O modules of the Siemens S7-1500 PLC.
- PLC programming for reading sensor values and controlling the chiller actuators.
- Configuration of an EPICS IOC communicating with the PLC via ISO-on-TCP using the s7nodave driver.
- Definition of EPICS Process Variables (PVs) corresponding to PLC variables and configuration of the Archiver Appliance and Grafana.
- Development of a PyQt graphical user interface for operator interaction [3].

The data and control flow is summarized as:

- Chiller sensors (temperature, pressure) → S7-1500 PLC (signal conversion and control logic);
- PLC control logic (PID, start/stop, cooling) → actuators;
- PLC → EPICS IOC (s7nodave, TCP/IP) → PV update;
- EPICS IOC → clients (GUI, Archiver) → monitoring and control;
- Archiver Appliance → short- and long-term storage
- Grafana → dashboard visualization via REST API;
- PyQt GUI ↔ EPICS PVs → operator commands and feedback;

This architecture ensures full transparency from physical sensors to digital analysis. Ethernet TCP/IP networking with fixed IP addresses and EPICS Channel Access (UDP discovery, TCP data transfer) provides deterministic and reliable HIL communication

4.2. EPICS Chanel Configuration and IOC Interface

The EPICS–PLC connection is achieved by defining IOC records that map directly to PLC memory areas. Two main record types were used:

Multi-Bit Binary Input (mbbi) for reading digital signals:

```
record(mbbi, "PLC:Flow_Switch") {
  field(DTYP, "s7nodave")
  field(INP,  "@PLC_IB0")
  field(SCAN, "I/O Intr")
}
```

Analog Output (ao) for writing numeric values (e.g., temperature set-points) to the PLC:

```
record(ao, "PLC:Q0_Setpoint") {
  field(DTYP, "s7nodave")
  field(OUT,  "@PLC_QB0")
  field(VAL, "25.0")
}
```

These records expose PLC registers as EPICS PVs, allowing real-time monitoring and controlled actuation through the Digital Twin.

4.3. Graphical User Interface (GUI)

The graphical interface was developed in PyQt (using QtDesigner for layout) and communicates with EPICS via dedicated PVs. It consists of four main panels:

- *Loop Monitoring* – displays real-time temperature, pressure and flow for L1, L2 and L3.
- *Set-points* – allows visualization and modification of reference temperatures (e.g., CHLR:L1:Setpoint).
- *Real-Time Plots* – continuously updated temperature trends.

The operator interaction with the cooling subsystem is performed through a PyQt-based graphical interface, shown in Fig. 1.

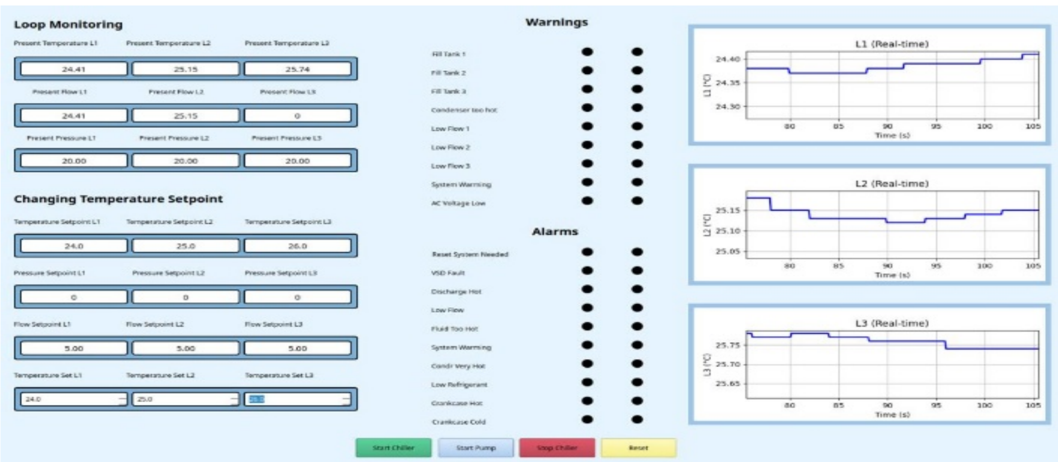

Fig. 1. PyQt-based GUI for the Mydax precision chiller, showing real-time monitoring of temperatures, pressures and flows for the three cooling loops (L1,L2,L3), as well as operator functions.

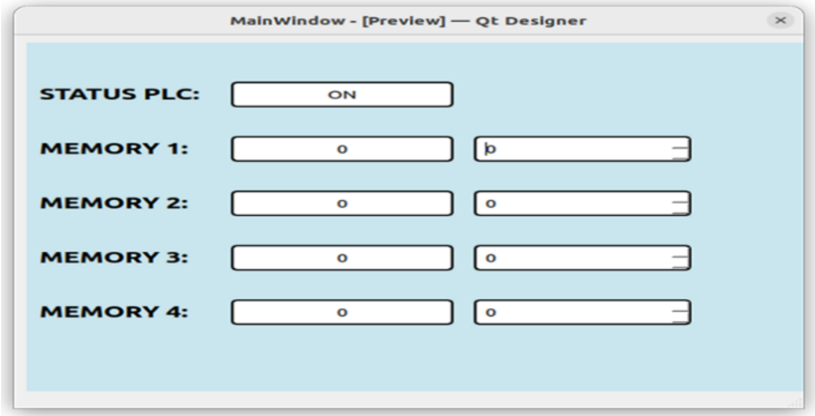

Fig. 2. PLC interaction panel designed in Qt Designer, illustrating direct access to internal PLC memory registers for monitoring and controlled write-back during Hardware-in-the-Loop operation.

Direct access to PLC memory registers during HIL testing is illustrated by the PLC interaction panel shown in Fig. 2.

The PLC communication status is displayed as:

ON – PLC online and communication active,

OFF – PLC offline or unreachable.

Each PLC memory register is shown with two fields: a read-only field for the current value and a writable field for injecting test values during HIL operation.

4.4. Experimental Results

During the experimental campaign, the Mydax precision chiller was operated under controlled conditions while connected to the Siemens S7-1500 PLC and the EPICS-based Digital Twin. Three cooling loops (L1, L2 and L3) were monitored simultaneously. Each loop has independent temperature, pressure and flow sensors, allowing the thermal behavior of the cooling system to be observed in real time.

A sequence of reference temperature set-points applied in the range 24°C–26°C, representing typical testing and operational conditions for accelerator subsystems. The set-points were written to the PLC via EPICS analog output (ao) PVs and processed by the PLC control logic, which adjusted the chiller actuators accordingly.

For each step change in set-point, the transient response of the three cooling loops was recorded. The data were captured at a sampling rate of 1 Hz and stored in the EPICS Archiver Appliance [4]. The temperature curves show smooth convergence toward the requested values, with no overshoot or oscillatory behavior. The steady-state deviation remained within ±0.2 °C, which is well inside the thermal stability requirements for accelerator operation.

Simultaneously, the operator GUI and Grafana dashboards displayed the live temperature, flow and pressure values. This dual visualization confirmed that the EPICS layer and the Archiver Appliance were synchronized with the PLC in real time, validating the correctness of the end-to-end data flow.

The real-time evolution of the cooling loop temperatures retrieved from the EPICS Archiver Appliance is shown in Fig. 3.

4.5. Grafana-Based Polynomial Regression and Stability Analysis

To quantitatively evaluate the stability of the cooling loops, the Grafana Polynomial Regression Plugin was applied to the archived temperature PVs. This plugin performs least-squares fitting of a polynomial function

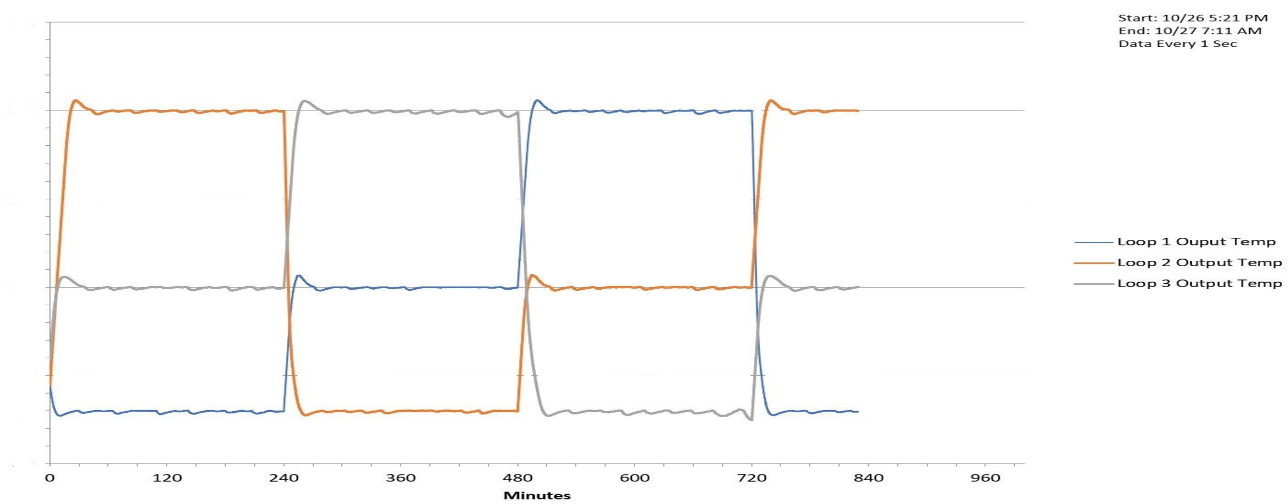

Fig. 3. Real-time temperature trends of the Mydax chiller cooling loops (L1–L3) retrieved from the EPICS Archiver Appliance, illustrating stable convergence to the applied temperature setpoints.

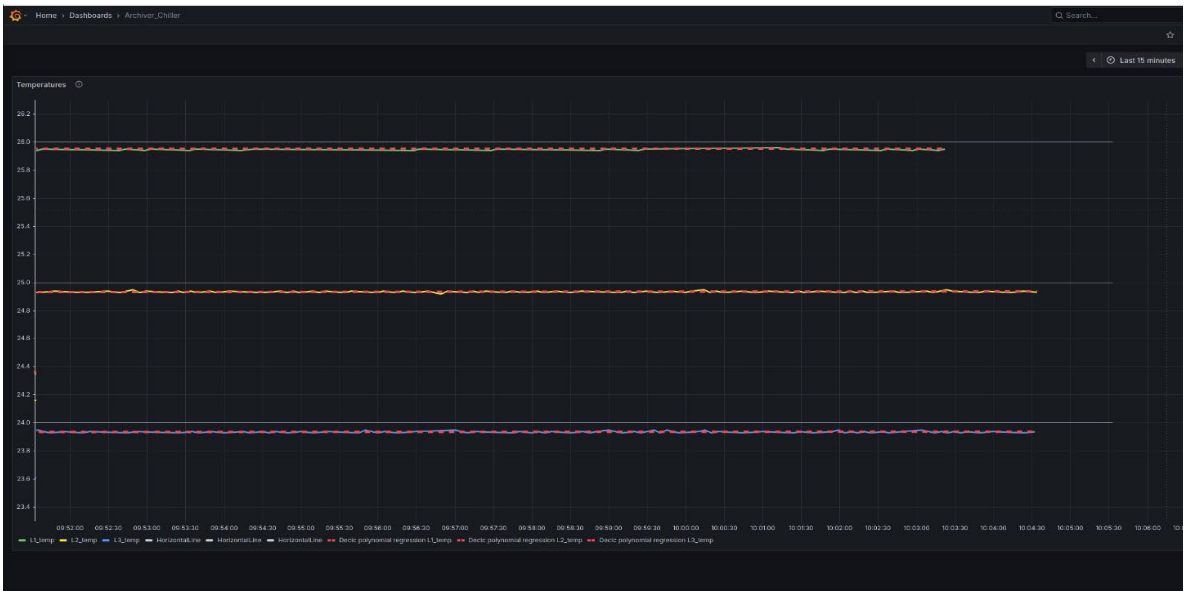

Fig. 4. Grafana dashboard showing polynomial regression–based stability analysis of the three Mydax chiller cooling loops, including measured temperatures, setpoints and regression trends used for long-term stability evaluation.

directly on the time-series data without requiring preprocessing in the data source [5].

Polynomial models of order up to $n = 10$ were used to capture both short-term fluctuations and long-term trends. The fitted curves were superimposed on the raw temperature measurements. The resulting regression profiles indicate that all three loops remain clustered around their respective set-points.

Stability and long-term behavior of the cooling loops were evaluated using polynomial regression analysis in Grafana, as shown in Fig. 4.

The regression analysis reveals two important properties:

1. *Long-term stability* – The slope of the fitted polynomial is close to zero for all channels, indicating the absence of thermal drift.
2. *Noise attenuation* – High-frequency fluctuations caused by sensor noise and control quantization are smoothed out, revealing the true thermal behavior of the system.

The multi-setpoint thermal regulation in order to validate the independent and stable control of multiple cooling loops:

$$T_{sp,1} = 24\ °C, T_{sp,2} = 25\ °C, T_{sp,3} = 26\ °C. \tag{1}$$

This configuration allows verification of loop decoupling and controller performance under non-uniform thermal conditions.

The real-time temperatures $T_i(t)$ of the three loops were acquired by the PLC and transmitted through the EPICS–Archiver–Grafana data chain. In Grafana, the signals were processed using a *decimated polynomial regression* algorithm, providing a smoothed digital-twin estimate of the thermal behavior:

$$\hat{T}_i(t) = a_0 + a_1 t + a_2 t^2, \tag{2}$$

where $T_i(t)$ represents the filtered temperature trend for each cooling loop: $i \in \{L1, L2, L3\}$.

The control performance for each loop is evaluated using the tracking error:

$$e_i(t) = T_i(t) - T_{sp,i}\ , \tag{3}$$

while thermal stability requires:

$$e_i(t) \approx 0 \ and\ \frac{dT_i}{dt} \approx 0. \tag{4}$$

The dashboard results show that both the measured temperatures and their polynomial regression estimates converge to the respective setpoints (24 °C, 25 °C, and 26 °C), with negligible deviation between $T_i(t)$ and $\hat{T}_i(t)$. This indicates a steady-state thermal regime with minimal noise and no observable oscillations or drift.

These results demonstrate that the Mydax chiller is capable of simultaneous and independent regulation of multiple cooling loops at different setpoints, confirming its suitability for MPS-critical accelerator subsystems. The close agreement between the physical measurements and the regression-based digital twin further validates the reliability of the HIL architecture for real-time thermal supervision and predictive protection.

A comparison between setpoints, measured temperatures and regression-based Digital Twin estimates is presented in Fig. 5.

This quantitative confirmation supports the conclusion that the Mydax chiller operates in a stable regime under EPICS-based supervision and that the Digital Twin accurately reflects the physical dynamics of the system [6].

4.6. Feedback Loop and Digital Twin Validation

The experimental setup implements a complete closed-loop Digital Twin, defined by the following data path:

Sensors → PLC → EPICS → Archiver & Grafana → EPICS → PLC.

This loop allows the Digital Twin to both observe and influence the physical system. In Hardware-in-the-Loop mode, simulated values or fault conditions can be

Fig. 5. Comparison between temperature setpoints and measured temperatures for the three cooling loops, including polynomial regression trends used as Digital Twin estimates of the thermal behavior.

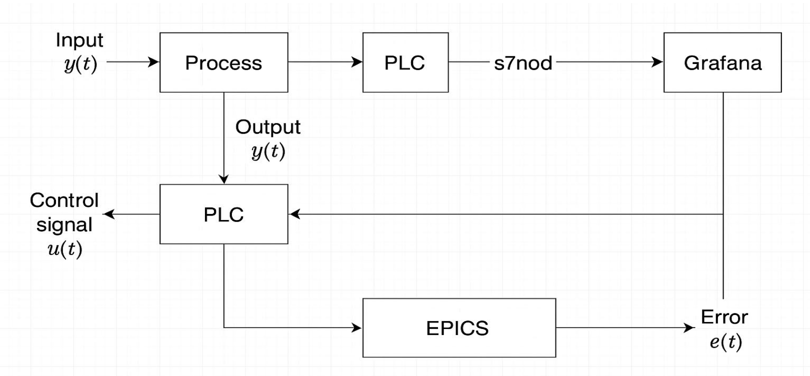

Fig. 6. Closed feedback loop implemented in the EPICS-based Digital Twin, illustrating bidirectional data flow between sensors, Siemens S7-1500 PLC, EPICS IOC, Archiver Appliance, Grafana analytics and control write-back during HIL operation..

injected into the PLC via EPICS output PVs, and the resulting MPS/PPS logic response can be monitored in Grafana and the GUI.

This capability is critical for safety-critical systems. It enables the validation of interlock logic, alarm thresholds and protective actions without exposing the real installation to risk. The Mydax chiller tests demonstrate that the Digital Twin is not a passive monitoring tool but an active validation and optimization platform.

The successful operation of the feedback loop confirms that the proposed EPICS-based Digital Twin architecture can serve as a foundation for future extensions such as predictive maintenance, machine-learning-based anomaly detection and adaptive safety thresholds.

The complete closed-loop Digital Twin architecture implemented for HIL validation is illustrated in Fig. 6

4.7. Communication Performance and Data Integrity

In parallel with the thermal performance evaluation, the full communication chain PLC → EPICS IOC → Archiver Appliance → Grafana was continuously monitored during the test campaign. The Siemens S7-1500 PLC remained in the ONLINE state throughout the experiment, with no observed communication interruptions, protocol errors, or data loss.

The system relied on a dedicated industrial Ethernet infrastructure, using managed switches and fiber-optic links between the control room and the equipment area. This network configuration provided low-latency, high-bandwidth, and EMI-immune communication, which is essential in the accelerator environment where strong RF fields and high-power electrical equipment are present.

Data exchange between the PLC and the IOC was performed using the S7 protocol (ISO-on-TCP) via the *s7nodave* driver. All EPICS Process Variables were updated at their configured scan rates and forwarded without missing samples to the Archiver Appliance. Historical data retrieved through Grafana showed full consistency with the real-time values displayed in the operator GUI, confirming correct operation of the Channel Access and archiving layers [7].

Command transmission was also verified. Start/stop and set-point commands issued from the GUI were delivered to the PLC with negligible delay and immediately applied by the Mydax chiller. The resulting changes in temperatures and operating states confirmed that the bidirectional EPICS–PLC communication path is sufficiently fast and reliable for control and protection-relevant functions.

A low-level EPICS IOC shell test script was used to validate deterministic bidirectional communication between EPICS and the PLC. Command bits were written using *dbpf*, while *readback* and status verification were performed using *dbpr*. This approach enabled direct validation of the control and feedback loop independently of higher-level GUIs.

 # List PLC-related PVs
dbl

 # Write command bits to PLC
dbpf PLC:WriteBit1 1
dbpf PLC:WriteBit 1

 # Reset command bits
dbpf PLC:WriteBit1 0
dbpf PLC:WriteBit 0

This script forces digital command bits from EPICS to the PLC, validating the command path of the control loop. The PLC executes the commands in real time, while feedback can be read through corresponding status PVs to close the loop and confirm correct operation.

5. FURTHER RESEARCH

The architecture presented here is intentionally compact, focusing on a single safety-relevant subsystem (the cooling chiller) to validate the integration concept. Future work will concentrate on:

- extending the PLC-EPICS-Archiver-Grafana chain to other subsystem (radio frequency, vacuum, access control);
- defining a common PV naming and structuring convention for all MPS/PPS-related signals;
- integrating basic data-driven anomaly detection on archived time-series, as a first step towards predictive maintenance;
- using the Digital Twin environment for training scenarios, where operators can explore fault conditions in a safe, HIL-based setup.

6. CONCLUSIONS

A practical, EPICS-based integration of PLC safety systems has been presented as a foundation for a Digital Twin implementation at the ELI-NP GBS facility. The proposed chain — Siemens S7-1500 PLC → s7nod → EPICS IOC → Archiver Appliance → Grafana — allows:

- real-time exposure of safety-relevant PLC variable as EPICS PV's;
- long-term archiving of process and interlock data;
- rich visualization and analysis through configurable dashboards.

The Hardware-in-the-Loop test with a Mydax precision chiller demonstrated that the architecture can monitor and validate the behaviour of a real cooling subsystem, while the safety logic remains fully under PLC control. The results confirm that the proposed approach is suitable as a Digital Twin backbone for safety systems and can be extended to additional subsystems of the accelerator facility.

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