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Investigation of Engineering Support Subsystems in the IIoT Context Using Telemetry Data

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***Abstract*— The functional zoning of a small- and medium-scale digital printing facility has been refined, taking into account the allocation of production and auxiliary areas with diverse operational purposes. The study focuses on the sensor infrastructure of IIoT-based technogenic support processes, which play a key role in maintaining safe and sustainable operation of printing equipment. The investigation was conducted using a unified learning bench built on the Arduino UNO platform, designed to emulate environmental monitoring and control subsystems. This bench serves as a training-oriented tool for developing professional competencies in industrial automation. The integration of telemetry with xJDF workflow coordination standards reinforces the inter-disciplinary approach to smart manufacturing environments.**

Keywords*— *Digital Printing Industry, Learning Bench Platform, Technogenic Support Processes, Xjdf, Industrial Internet Of Things.

I. Introduction

The advancement of Industrial Internet of Things (IIoT) technologies and cyber-physical systems has brought significant transformations to industrial automation, particularly in the education and training of engineering personnel. Bench emulators, serving as tools for modeling real industrial processes, play a pivotal role in developing practical skills among technical students by enabling experimentation with sensor networks, communication protocols, and control systems within a controlled environment. In the context of specialized sectors such as printing, where IIoT can optimize order fulfillment and enhance production safety and sustainability, the demand for tailored learning benches is especially pronounced.

The use of bench emulators such as Mininet and GNS3 within the Cyberinfrastructure Laboratory for training students to work with high-speed networks and programmable switches enables the modeling of network protocols including MQTT, OPC UA, and IoT devices, as well as the analysis of telemetry data, which is highly relevant for IIoT [1].

Deep learning applications in IIoT incorporate hardware-in-the-loop (HIL) platforms to simulate sensors and actuators in real time. HIL emulators facilitate industrial system testing, including telemetry and predictive maintenance [2]; in the context of professional training, HIL platforms allow students to work with real data under simulated conditions for production metrics analysis and machine learning algorithm testing.

The application of HIL in preparing engineers to work with industrial systems in automotive, energy, and mechatronics sectors combines hardware (FPGA, DSP) with real-time simulation for controller testing [3], enabling students to model electric drives, power systems, and controllers, test control algorithms, and analyze telemetry data in a safe environment.

IIoT standardization testbeds simulate real-world industrial scenarios, including telemetry, for testing data structures and hardware platforms [4], allowing students to experiment with IIoT protocols and analyze telemetry data, thereby contributing to engineering education.

However, existing open-access sources primarily focus on general engineering competencies and do not emphasize the preparation of specialists for niche industries such as printing. There is a lack of methodologies or educational modules that utilize bench emulators for modeling industry-specific cases. Furthermore, the use of bench emulators to model technogenic support processes and subsystems in the preparation of print orders is not sufficiently explored [5, 6]. Therefore, the design of a laboratory bench integrating aspects of automation, materials science, electronics, and programming will enable the training of specialists who understand the entire cycle of executing a print order—from substrate selection to post-processing—while minimizing risks and waste in production. The growing demand for automation and digitalization in printing, as well as the need for specialists proficient in IIoT technologies, makes this research highly relevant within the context of Industry 4.0. The learning bench will serve as a tool for preparing competitive engineers capable of addressing modern challenges. This aligns with global trends in sustainable development, industrial process safety, and contemporary labor market demands.

II. Engineering and Environmental Dimensions of the Print Order Life Cycle

A typical printing enterprise is characterized by considerable technological diversity, driven by a wide range of products that must be manufactured to meet individual customer requirements while ensuring print quality parameters, substrate compatibility, and subsequent post-print processing. Accordingly, the production environment develops a structure of functional zones that reflects the sequential stages and specialization of the printing process.

A. Refined Zoning of the Production Environment in Operational Printing

In the *prepress segment*, zones related to print preparation are allocated. These include areas for order reception and technical specification storage, graphic layout processing, editing and printing output, as well as spaces for storing paper, films, inks, and consumables. Separate workstations for color correction and digital proof printing may also operate independently. Such zones not only ensure informational and material preparation but also require regulated conditions regarding humidity, temperature, and lighting, which affect the stability of digital equipment operation and the accuracy of color reproduction.

The *printing segment* encompasses zones where the image application process is directly performed. In the case of a digital printing facility, this may involve laser or inkjet machines of either sheet-fed or roll-fed types. Depending on the scale of production, one or multiple printing lines are organized. These areas require a controlled microclimate, particularly regarding temperature, humidity, and ventilation, as well as exhaust systems when using finishing varnishes or toners. Auxiliary devices such as feeders, dryers, and thermal fixation systems may be located near the machines.

The final processing of printed products takes place within a series of production zones grouped into the *post-press segment*. This area may include cutting machines, folding and binding equipment, heat presses, laminators, and packaging machinery. Each of these operations is performed in a separate functional zone with specific working condition requirements—such as dust control, temperature stability, or exhaust ventilation. Additionally, within the post-press infrastructure, areas for labeling, sorting, storage, and shipment of finished products are organized.

Such a separation of processes ensures a logical sequence of operations, minimizes the intersection of technological flows, and enables efficient organization of the internal environmental monitoring system. Within each zone, distinct sensor support profiles may be applied to correspond with the specific equipment and technological load. Accordingly, given the refined zonal structure of a printing enterprise, sensor support cannot be standardized, since operating conditions, types of performed operations, and impacts on the microenvironment significantly differ among production areas. The application of contextual sensor support profiles allows for consideration of each zone's specifics, including thermal, dust, gas, or noise loads, as well as machine operating modes and personnel interactions.

In some zones, temperature and humidity stability are critical, while in others effective air exchange or dust control is paramount. In accordance with this, sensor configurations must be adapted to the functional purpose of the area, ensuring accurate and timely detection of deviations from optimal conditions and providing a basis for subsequent automation and analytics. This approach contributes to increased reliability, quality assurance, and the creation of a favorable production environment. Therefore, the zonal organization of the printing environment necessitates specialized sensor support that reflects the technological load and operating conditions of equipment in each area. Such zoning enables proper alignment of sensor subsystems with technological processes, ensuring a justified structuring of technogenic support.

B. Delineation of Technogenic Support Subsystems i Print Order Preparation

Within the structure of a printing enterprise, technogenic support subsystems encompass a set of sensor control tools, algorithmic management, and actuating automation elements designed to maintain environmental parameters that accompany the main technological processes. These subsystems are divided into several functional groups (Table 1): microclimate control (temperature, humidity, air exchange), concentration parameter monitoring (CO_2, smoke, vapors), dust load observation, spatial operation monitoring (open doors, covers, operator presence), and auxiliary infrastructure management (ventilation, lighting, alarm systems). The alignment of these subsystems with the zonal organization of the enterprise enables adaptation of sensor configurations to the specific features of each area.

TABLE I. DEFINITION OF TECHNOGENIC SUPPORT SCENARIOS

Scenario	Active Zone	Sensor Types	Response Logic
Intake and preflight of layout	Prepress preparation	Temperature, humidity, LDR	Lighting tuning for color control, environment stabilization
Print job setup	Prepress preparation	Presence, temperature	Operator detection, activation of feed/warm-up systems
Monochrome print run	Digital printing	Humidity, CO_2, noise	CO_2 response: venting, cooling, acoustic diagnostics
Full-color printer operation	Digital printing	CO_2, temperature	Exhaust activation under heating, emission monitoring
Web substrate drying	Drying	Temperature, dust	Exhaust speed adjustment, contamination alert
Fan overload detection	Drying	Current, dust	Process shutdown, operator notification
Sticker lamination	Postpress	Temperature, vibration	Overheat protection, platform stabilization
Small-run packaging	Packing / warehousing	Light level, presence	Local lighting activation upon motion detection
CO_2 check in storage area	Packing / warehousing	CO_2, humidity	Exhaust activation, access limitation

In substrat storage zones, sensor support focuses on stabilizing temperature and humidity. Considering the sensitivity of paper and films to fluctuations in these parameters, it is advisable to use combined digital sensors (e.g., DHT or SHT) directly connected to the controller. Control may be limited to indication or automatic activation of ventilation/heating based on threshold values. The controller executes a scenario for maintaining long-term storage conditions without the need for constant operator intervention.

At the prepress stage, particularly in areas handling graphic files or proof printing, the use of light sensors (LDR) combined with temperature sensors is recommended. This enables maintaining a visually stable environment for image assessment. Actuating devices such as lighting control modules or blinds with pre-calibrated illumination settings may be employed.

In printing zones where solvent-based wide-format inkjet printers are operated, the sensor infrastructure must cover temperature, humidity, CO_2 levels, and air exchange intensity control. The use of gas sensors such as MQ series, combined with temperature and humidity sensors, enables monitoring parameter changes during equipment operation. Exhaust fans can be controlled via transistor or relay switches, with smooth speed regulation implemented through PWM when applicable. Data processing is performed by a microcontroller with connectivity options for serial monitoring or display.

The drying zone involves heat sources and an increased risk of localized overheating. In such cases, temperature sensors are placed near heating elements as well as in exhaust ducts. Additionally, dust sensors or analog devices (potentiometers with manual simulation) are employed. The exhaust system requires control based on temperature and air quality. The controller architecture allows prioritizing parameters within activation scenarios.

In the post-press zones, where cutting, folding, laminating, and other operations are performed, the sensor system must account for both microclimatic parameters and load indicators. Position sensors, photoresistors, or vibration modules may be used to monitor machine status. Additionally, dust and temperature sensors are advisable to assess the impact of thermal processing or mechanical shredding. Actuating elements primarily include ventilation modules or visual alarms. In packaging, storage, and shipping areas, control focuses on CO_2 levels, temperature, lighting, and personnel presence. Simple devices such as PIR sensors and photoresistors enable activation of lighting or alarms upon motion detection. Control is implemented via a microcontroller with pre-programmed response logic.

Overall, this structured allocation of sensor devices and actuators according to the enterprise's zonal division enables the formation of an adaptive technogenic support system tailored to the specifics of print order preparation and execution. The use of energy-efficient microcontrollers, basic reading protocols, and simple response algorithms ensures integration flexibility and the possibility of modification for specific production scenarios.

III. Development of Unified Learning Bench

In modern printing production, technogenic parameters of the microenvironment, energy consumption, load, and spatial organization are increasingly integrated into the end-to-end xJDF production workflow as industrial metrics accompanying the life cycle of a print order. To study the sensor infrastructure capable of generating such indicators within a zoned production organization, the presented project implements a unified learning bench based on the Arduino UNO microcontroller.

A. Sensor Infrastructure Hardware for Multizonal Technogenic Support

The bench architecture enables the sequential activation of individual technogenic support subsystems (Fig. 1), simulating operation within IIoT scenario logic by recording parameters corresponding to real printing environment conditions (Table 1). The hardware is focused on emulating the basic functions of a sensor infrastructure capable of capturing technogenic microenvironment parameters within the zonal organization of the printing process. The purpose of the bench is to create conditions for stepwise reproduction of industrial monitoring logic using typical sensors suitable for integration into microclimate control systems. The functions of data acquisition, processing, and routing are implemented based on the Arduino UNO R3 microcontroller, which provides the necessary peripheral compatibility with digital and analog sensor modules. Microclimate parameters are transmitted via the digital temperature and humidity sensor DHT22, which delivers stable output data with high resolution and requires no complex calibration.

To detect carbon dioxide concentration, the MH-Z19B sensor is employed, operating on the principle of non-dispersive infrared (NDIR) measurement and transmitting data via a UART interface. This module enables modeling of adaptive ventilation scenarios based on input load within the simulated zone.

Simultaneously, dust concentration is monitored using the optical sensor GP2Y1010AU0F, which determines particulate matter concentration based on light scattering. Within the scope of the educational experiment, this component allows simulation of risks associated with elevated aerosol levels, particularly when working with toner, varnish, or paper dust.

To simulate automated responses to operator presence, a PIR sensor module HC-SR501 is used. Utilizing an infrared receiver, this sensor detects motion of objects with characteristic thermal radiation, enabling the implementation of conditional activation logic for zone service subsystems. The actuator component of the bench consists of a 5V DC fan controlled via a transistor switch. This setup allows for basic ventilation on/off algorithms based on sensor data while maintaining electrical isolation between the power circuit and the microcontroller.

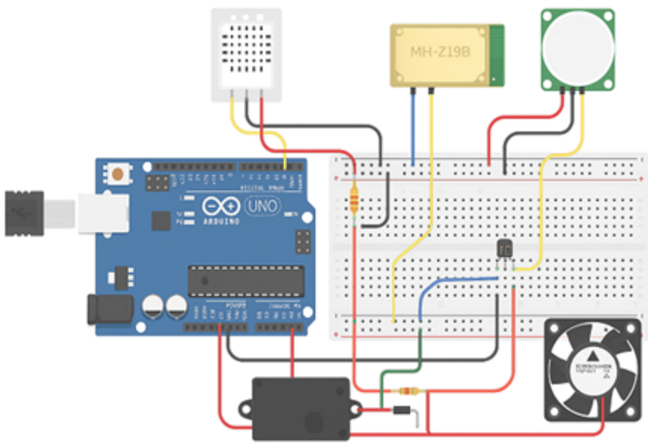

Fig. 1. Wiring diagramm of unified learning bench

Thus, the component architecture of the bench forms an approximate scheme of sensor data acquisition, logical analysis, and actuator response, enabling pedagogical simulation of real production telemetry behavior based on xJDF specifications. This approach provides contextual reconstruction of technogenic processes relevant to the production cycles of printed materials.

B. Design and Embedding of the Final Web Terminal

The identified relevant industrial technogenic support metrics are structured as part of the information model describing variable production environment parameters within zoned organization of the enterprise, including microclimate indicators, energy consumption, spatial load, temperature stability, and airborne dust levels. Within the xJDF framework, these parameters are represented as specialized attributes of nodes such as `<AuditPool>`, `<ResourceLinkPool>`, and extended tags like `<EnvironmentMetrics>`, integrated at JobPart hyper-tag level, which corresponds to specific technological operations or functional zones.

Descriptive extraction of these metrics is performed through service preprocessing procedures or xJDF workflows that transform sensor readings into a standardized key-value format suitable for visualization of IIoT infrastructure on simulator's web panels.

Further routing of telemetry received by the server within the zoned technogenic support structure is implemented via a UART serial interface, providing data transmission to computational core of Arduino UNO-based learning bench. Within the bench, the Arduino UNO hardware serial port (TX/RX) is connected to the virtual COM port of laboratory computer via a USB-UART bridge operating in Communications Device Class mode (Fig. 2).

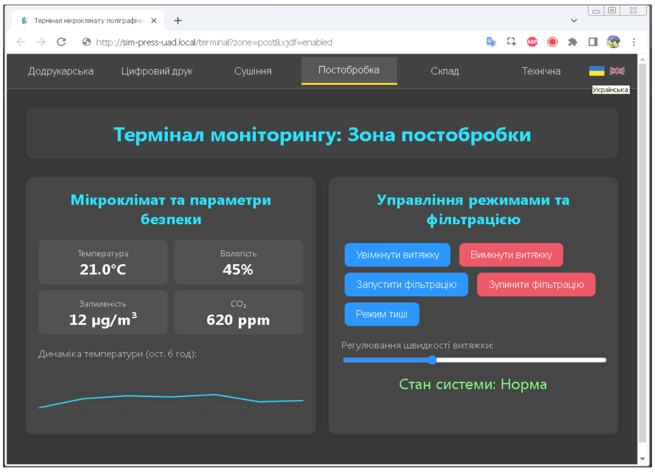

Fig. 2. Tab of Approximated Telemetry for the Post-Processing Zone on the Emulator's Web Panel Hosted on the University Server

The parameters obtained in this way during the enabled xJDF support mode are transmitted to the university server within the local laboratory environment at the address `http://sim-press-uad.local/terminal/#`, where a mechanism for preprocessing, aggregation, routing, and buffering of sensor messages related to the multizonal technological support infrastructure of printing production is implemented. Data transmission is performed in a textual format with a fixed delimiter structure (e.g., for Fig. 2 key=value pair: `TEMP=21.0; HUM=45;CO2=620;PM=12; ZONE=post`), after which the data are parsed on the microcontroller and used in real time to control simulated actuators such as LED indicators, drive simulators, control panels, and digital feedback sensors. These components collectively enable scenario-based responses of the zoned print shop climate control system. The integration of individual sensor scenarios, implemented through the designed unified bench, provides a subject-informational environment for hardware emulation aimed at mastering engineering disciplines with a printing specialization. This setup allows students to directly interact with digital twins of technogenic support subsystems during the preparation of print orders.

Consolutions

The generalization of sensor infrastructure configuration scenarios within the zonal division of the printing enterprise enabled the investigation of typical and approximated technical solutions used to maintain microenvironment parameters across various production segments. The identified correspondence between the nature of technological load and technogenic monitoring tools served as foundation for developing a simulation model capable of reproducing key functional characteristics of real subsystems within an interdisciplinary educational platform. This model establishes a basis for pedagogical reconstruction within a unified bench, which integrates individual sensor scenarios into IIoT logic structures for mastering profession-oriented disciplines.

The designed educational bench for monitoring technogenic support subsystems in digital printing can be utilized to implement elements of predictive maintenance, forecasting the condition of ventilation systems, detecting air exchange disruptions, filter clogging, or exceeding sanitary threshold parameters of the microclimate. Despite the use of simplified hardware, the presented bench enables obtaining reliable results through the integration of approximated parameters based on real industrial telemetry. This ensures not only a high degree of accuracy but also the possibility of preliminary testing of adaptive control scenarios under conditions approximating the real production environment. The modular structure and IIoT compatibility provide adaptability of the bench to changes in production process and enhance the overall relevance of the educational content.

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