Enabling Digital Threads for Smart Cities and e-Health: The Intelligent Infusion Bag Case

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***Abstract*—This paper presents a proof-of-concept for an Intelligent Infusion Bag, designed to demonstrate the potential of Digital Threads in smart healthcare scenarios. The prototype leverages low-cost printed sensorisation to enable continuous monitoring of the bag's lifecycle—from production and storage to patient administration. By collecting and integrating data such as environmental conditions, usage tracking, and synchronised patient information, the system supports advanced features like automated safety checks, adherence to medical prescriptions, and human error reduction. Although only partially realised as a physical product, the demo focuses on the underlying data architecture and service interactions, highlighting how such solutions can enhance healthcare delivery within broader Smart Cities and Communities contexts.**

***Index Terms*—Service-oriented architectures, Digital Thread, Smart Cities, Smart Products, Smart Healthcare**

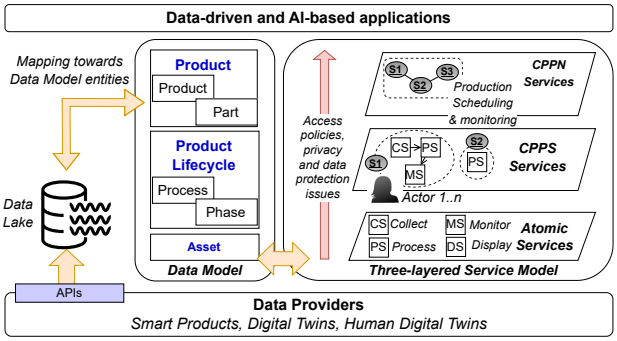


Fig. 1: Service-oriented architecture for Digital Threads.

I. Introduction

The advent of Smart Products within Smart City ecosystems has underscored the necessity for digital infrastructures capable of supporting lifecycle-wide data acquisition, integration, and semantic interoperability. Central to this vision is the notion of the Digital Thread, which enables the continuous and contextualised flow of information across the various stages of a product's lifecycle. When combined with the Internet of Services (IoS) paradigm, Digital Threads not only facilitate data traceability and process transparency, but also support the orchestration of dynamic, cross-organisational services [2], [1].

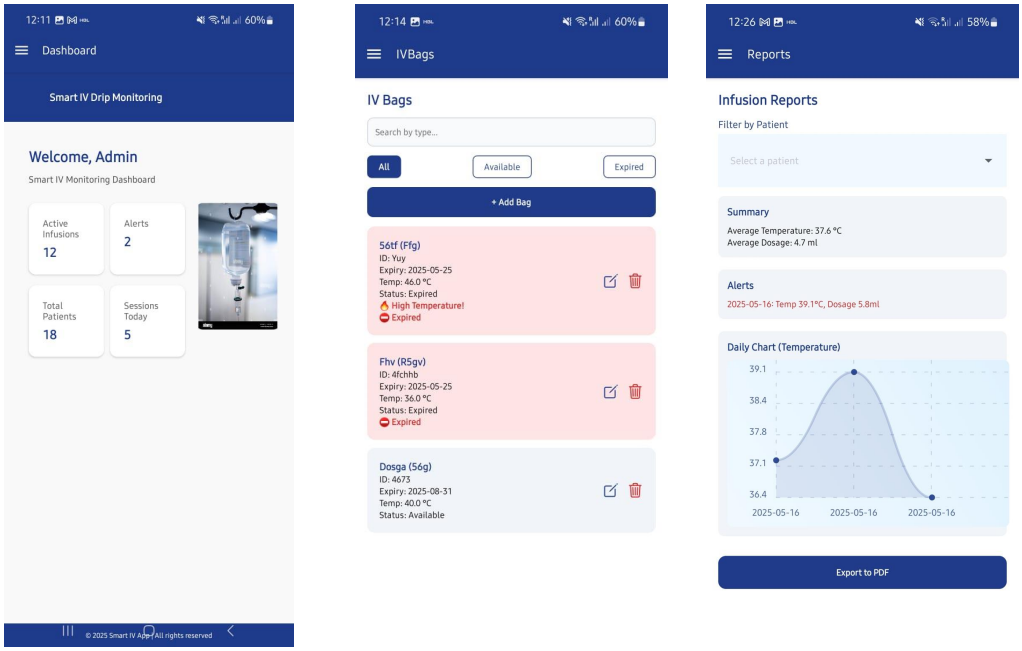
In healthcare domains, this conceptual framework acquires particular relevance, as medical products are increasingly expected to exhibit intelligent behaviours and to participate in interconnected service ecosystems. In this context, Smart Infusion Bags represent a paradigmatic case of digitally augmented medical devices, enhanced through low-cost printed sensorisation and real-time data services. By embedding such artefacts within a Digital Thread infrastructure, it becomes possible to enable novel functionalities—such as prescription validation, anomaly detection, and lifecycle-aware decision support—thereby improving patient safety, reducing human error, and fostering a more sustainable and accountable healthcare system. In scientific literature, while deep learning and IoT-based solutions show promise [4], [3], they often suffer from restricted compatibility, limited automation, and lack of integration with hospital systems (e.g., EMRs).

This study, developed within the framework of the MICS (Made in Italy – Circular and Sustainable) Extended Partnership, introduces a proof-of-concept demonstrator that leverages Smart Infusion Bags to exemplify the implementation of a Digital Thread in a real-world healthcare scenario. The proposed architecture (Figure 1) adopts a modular, multi-tier design to address key challenges such as data heterogeneity, sovereignty, and interoperability. It comprises: (i) a Data Providers and Data Lake tier, collecting sensor data from Smart Infusion Bags and external sources (e.g., healthcare information systems, wearable devices on patients) using schema-on-read approaches; (ii) a Multi-perspective Data Model tier, encoding the semantics of products, lifecycle phases, and actors under data governance constraints; (iii) a Three-layered Service Model, organising services across product, process, and stakeholder views to enable cross-institutional coordination; and (iv) a Data-driven Applications tier, which supports AI-powered analytics for lifecycle monitoring, anomaly detection, and prescription verification. Grounded in a concrete healthcare use case, this architecture illustrates how digitally enhanced medical products can become active nodes in intelligent, trustworthy data ecosystems—advancing the vision of Smart Cities, digital health, and sustainable innovation.

II. Smart Infusion Bag Demonstrator

The Smart Infusion Bag demonstrator showcases the following capabilities:

- **Lifecycle Tracking**: Trace and collect data across all stages of the infusion bag lifecycle, from production and storage to administration and disposal.



(a) (b) (c)

Fig. 2: The Smart Infusion Bag GUI: (a) nurse view; (b) operator view; (c) medical doctor view.

- **Environmental Monitoring**: Detect if the bag has been stored or used under improper conditions (e.g., exceeded temperature thresholds).
- **Patient Correlation**: Link the bag to the patient's profile to synchronise sensor data with vital parameters.
- **Human Error Reduction**: Validate usage conditions against digital prescriptions, alerting caregivers in case of discrepancies (e.g., incorrect dosage, expired bag).

The *Smart Infusion Bag* system transforms a standard IV drip into a *Smart Object* through the integration of a fully printed, non-contact, passive capacitive sensor for fluid level monitoring. The sensor, printed directly on the IV bag and coupled with a coil, enables the generation of a resonant frequency that correlates with the fluid level. The system architecture consists of three core components: (i) *sensing element*, a resonant capacitive sensor that enables real-time, non-invasive monitoring of fluid levels; (ii) *reader electronics*, a custom-designed PCB interfaces with the sensor using Direct Digital Synthesis (DDS) and an Arduino Nano IoT microcontroller that manages the signal acquisition through its 12-bit ADC and transmits the processed data via Bluetooth Low Energy (BLE); (iii) *data acquisition and communication unit*, where a raspberry Pi receives BLE data, stores it locally, and relays it to a web server for integration with higher-level systems.

To support a variety of users throughout the product lifecycle, three tailored front-end interfaces have been developed using React.js: (a) *nurse interface*: a real-time application tailored to hospital staff, providing a comprehensive overview of all active infusion bags (Figure 2(a)); (b) *operator interface*: designed for technicians and supply chain managers, this interface offers lifecycle traceability of each Smart Infusion Bag (Figure 2(b)); (c) *medical doctor interface*, focused on clinical decision support, to correlate infusion data with patient profiles (Figure 2(c)).

III. Concluding Remarks and Research Challenges

The Smart Infusion Bag demonstrator aligns with the CINI National Lab architecture for Smart Cities, showcasing how service-oriented technologies can support healthcare innovation. Future developments will explore demand-driven service composition, LLM-based service orchestration, and integration with urban healthcare and emergency systems. This work illustrates how a basic medical consumable can evolve into a smart, networked device, enabling personalised care, real-time monitoring, optimised logistics, and data sovereignty. As such, it contributes to more sustainable, AI-driven healthcare within smart community ecosystems.

References

[1] Tasnim Abdel-Aty and Elisa Negri. Conceptualizing the digital thread for smart manufacturing: a systematic literature review. *Journal of Intelligent Manufacturing*, pages 1–25, 2024.

[2] Massimiliano Garda Francesco Leotta Massimo Mecella Anisa Rula Devis Bianchini, Tiziano Fapanni and Emilio Sardini. Digital thread for smart products: A survey on technologies, challenges and opportunities in serviceoriented supply chains. *IEEE Access*, 12:125284–125305, 2024.

[3] Disha Zhu Xiaoyan Jin Shaomei Shang Xuefeng Wang Weiran Xu, Luoya Hou and Hongbin Han. Development of smart infusion pumps: state of the art and future perspectives. *Interdisciplinary Nursing Research*, 2(2):107–111, 2023.

[4] Min Jae Kim Young Jun Hwang, Gun Ho Kim and Kyoung Won Nam. Deep learning-based monitoring technique for real-time intravenous medication bag status. *Biomedical Engineering Letters*, 13(4):705–714, 2023.