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(Article begins on next page)

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Monitoring Data Streams in Industry 5.0: a Knowledge Graph approach

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***Abstract*—In the landscape of Industry 5.0, Internet of Everything (IoE) networks are emerging as crucial components for connecting diverse industrial sensors and devices, going beyond the typical Internet of Things (IoT) boundaries to include people, processes, and data. This expanded scope brings forth unprecedented opportunities for enhanced collaboration and efficiency in industrial settings. On the other hand, due to the need to integrate disparate and heterogeneous devices and data sources, it also introduces both technical and semantic interoperability challenges for meaningful and shared data interpretation and exchange. This paper outlines an architecture for gathering and monitoring semantic data streams in IoE environments, which addresses semantic interoperability through an integrated representation of sensor metadata, locations, preferences, right accesses, tasks and responsibilities in an Enterprise Knowledge Graph. Developed within the HOMEY project, the approach enables dynamic stream monitoring, data querying and exploration, and aims to lay the groundwork for a robust industrial human-centric framework supporting IoE applications.**

***Index Terms*—Data Stream, Industry 5.0, IoT, Metadata, Knowledge graph**

I. INTRODUCTION

Industry 5.0 represents a paradigm shift in manufacturing and industrial operations, focusing on human-robot collaboration, personalized mass production, and seamless connectivity across the entire value chain [1]. Central to this transformation is the efficient monitoring of data streams generated by various sensors, machines, and devices deployed in industrial environments. However, the dynamic nature and scale of data streams pose significant challenges, including scalability, real-time processing, data quality, anomaly detection, and security, necessitating innovative approaches for real-time analysis and decision-making. This holds both in Internet of Things scenarios, where sensors and smart objects are capable to interact through the network, as well as in the recent landscape of the Internet of Everything (IoE). This term characterizes a scenario which sees the integration of devices and machines along with people, processes, and data into a unified network. IoE industrial environments are characterized by pervasive connectivity and intelligence, seamless communication, collaboration, and automation across various domains, with a human-centric approach towards sustainable and optimized use of resources.

In this setting, the capability to integrate heterogeneous data coming from multiple sources, e.g. traditional sensors, wearable devices, smart objects, process management and monitoring systems, is a requirement to achieve a full integration and support advanced tasks. A step towards this goal is the achievement of technical and semantic interoperability. While the former aspect is focused to network protocols, interfaces and operating standards, the latter aims to define a higher abstraction layer capable to support meaningful data exchange and interaction [2]. This is often realized through shared reference data models (in the form of ontologies or vocabularies), which provide mutually understood meaning for entities in the IoE.

In this work, we outline the key features of an architecture for semantic interoperability in an IoE scenario, based on a Enterprise Knowledge Graph, and show its application for gathering and monitoring of data streams. The approach, designed in the context of the HOMEY project[1], aims to lay the groundwork for the construction of a fully-fledged industrial framework supporting IoE applications.

As a case example, in this work we refer to an industrial scenario with a smart Heating, Ventilation and Air Conditioning (HVAC) system. This includes a number of sensors and smart objects measuring various parameters, such as temperature, humidity, pressure, position, vibration, airflow, air quality to detect contaminants in the air, e.g. particulates, pollutants and noxious gases that may be harmful to human health. The system is designed to maintain temperature and humidity at comfortable levels, but also to monitor levels of air pollution based on a set of preferences. Please note that different industrial areas may require tailored environmental settings, based on specific criteria: a manufacturing room with heavy machinery might necessitate higher ventilation rates, along with appropriate temperature levels to ensure both air quality and comfort; office spaces might be focused primarily on

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[1] https://homey-prin22.unipv.it/

temperature control but also on regulating the concentration of gases, which are naturally produced by breathing, to maintain a comfortable and healthy work environment. The monitoring system may also integrate data from some informational subsystems, which provide dynamic rules that may change over time based on evolving requirements. Moreover, this system may be monitored and controlled by users, either with a controller or other forms of more complex interactions, such as voice or gestures, and/or through the above-mentioned network of smart objects. The use of a range of sensors producing data in different formats, schemas, and communication protocols highlights a significant integration challenge faced in IoE ecosystems. The present study aims to explore and propose solutions to achieve a seamless data gathering and integration.

The rest of the work is structured as follows: Section II surveys relevant Literature on solutions for interoperability in IoT/IoE environments. The data model and the architecture of the framework are introduced in Section III, while Section IV focuses on the monitoring approach and possible applications. A discussion of future work concludes the paper in Section V.

II. RELATED WORK

In the context of IoE infrastructures, the complexity and diversity of devices and systems necessitate innovative data storage and management models. To efficiently handle the continuous influx of sensor data, various research efforts have converged on hierarchical and layered architectures, where a "layer" is a distinct level of the architecture performing specific functions, such as data collection, processing, storage, or application support. In [3], authors introduced a three-level storage architecture for Industry 4.0, where the layer distinction is based on access frequency to stored data. Similarly, the authors of [4] proposed a model for Sustainable Smart Cities (SSC) with an additional edge and fog layer to enhance local processing and minimize cloud dependency. The work described in [5] discusses an architecture that incorporates AI for data analysis. In [6], authors presented a structure for cognitive factories in Industry 5.0 with a focus on data collection, network management, service support, and application development, while in [7] authors added a fifth Business Layer to the SSC model to address regulatory frameworks for sustainable urban development.

The integration of Knowledge Graphs (KGs) within IoT architectures is increasingly recognized for enhancing data management and analysis [8]. An application of KGs in industry is demonstrated in [9], showcasing their use in adapting production lines to meet dynamic customer demands. Authors defined two ontologies for product characteristics and production capabilities and presented the Manufacturability Analysis (MFA) software, that performs queries to find suitable production lines. Their work also addressed the semantic interoperability issue due to the heterogeneous data collected by different organizational units (e.g., identical names for entities with different meanings). The same issue is addressed in [10] where authors focus on constructing a KG for the development of an information retrieval system: they employed text mining techniques for preprocessing raw data, defined nodes and relationships within the KG, and used centrality metrics to bridge semantic gaps, thereby providing contextual and interconnected term identification. An approach to model an Industrial Control System (ICS) as a KG, representing each device as a node and interactions as relationships is presented in [11]. Authors highlight that this modeling enables detailed tracking of sub-events during fault occurrences, and provides a support to fault diagnosis and operational detection through knowledge reasoning. They emphasized the critical importance of ensuring security defenses, which is one of the main challenges in current IoT infrastructures. Similarly, anomaly detection techniques, such as behavioral fingerprinting [12], can be used to enhance security and robustness in IoT systems. They aim to identify unusual patterns and deviations in the data produced by smart objects, starting from a model of the expected interaction behavior of smart devices.

Regarding interconnectivity, a significant contribute is described in [**?**], where authors proposed a semantic IoT architecture introducing a "Semantic Gateway as Service (SGS)", which is situated between physical-level sensors and cloud-based services and adds semantic annotations to raw sensor data. Ontological models can be utilized to semantically enrich the MQTT protocol, which mandates precise syntactic naming for topic subscriptions but lacks built-in discovery capabilities. Among the approaches, the "Semantic Subscription" (SembSub), presented in [13], achieves syntactic decoupling through ontology-based search, identifying semantic relationships and proposing optimal topic matches. Another approach presented in [14] automates industrial data subscription by generating sets of semantically similar topics for new sensors. Lastly, to address inaccuracies in MQTT's semantic representation, a structured framework called "RulE-BasEd WEb Editor for Semantic-aware Topic Naming in MQTT (MQTT-4EST)" was illustrated in [15]: it provides a user-friendly GUI, an ontology service, and a topic tree service to ensure valid topic structures, guiding users with ontology-based suggestions. These efforts highlight the potential of semantic models to enhance the functionality and interoperability of IoE systems using MQTT.

In summary, the described solutions mostly focus on traditional IoT scenarios, primarily involving sensors as main data publishers. However, Industry 5.0 encompasses use cases where also smart objects, people, processes are part of the data ecosystem and new data sources can be dynamically added, each with potentially heterogeneous communication protocols and data schemas. To the best of our knowledge, the HOMEY project is the first to address Industry 5.0 interoperability through an Enterprise Knowledge Graph and a human-centric approach. Unlike other solutions, the KG is specifically designed for an IoE environment, where data streams are semantically enriched. Additionally, it allows for role-based access control, ensuring that only contextually relevant data is provided, aligning with a human-centric approach.

III. MONITORING FRAMEWORK

In this section, we summarize the data model of the framework and the high-level architecture for data gathering and monitoring.

A. Data model

In order to achieve a semantic interoperability of devices, a characterization of the data recorded by devices or produced by IT (sub)modules is required through a machine-understandable representation. To this aim, and to provide a full contextualization of information produced by a device within the industrial IoE ecosystem, the data model of the platform relies on an Enterprise Knowledge Graph. The KG is aimed to provide an integrated, homogeneous view of the knowledge involved in the IoE environment, including description of metadata about sensors and smart objects, their deployment in the organization environment, locations, rights and preferences of employees on devices, their tasks and responsibilities.

The KG exploits the terminology defined in SemIoE [16], an OWL2 ontology designed to provide a structured and standardized way to describe entities and their relationships, fostering interoperability and enhancing the semantic understanding of IoE environments[2]. The ontology reuses and integrates several external modules to model specific aspects, most notably the W3C Semantic Sensor Network (SSN) ontology [**?**] for the definition of technical aspects of sensors and actuators. For the purpose of this work, we summarize the main classes of SemIoE that are involved in data gathering and monitoring:

- an *Agent*, either a employee or a *Smart Object*, is located in a *Site* within the organization, e.g. a room which is turn is located in a given floor, and may be involved in *Activities* of a *Process*, e.g., maintenance of the ventilation system;
- a Smart Object is composed by one or more *Systems*, e.g. a CO_2 sensor or a damper actuator for ventilation. Each system, according to the SSN ontology, is characterized by a set of technical *Properties* and relative conditions;
- a system is provided with the specification of the format and the protocol of the produced data. For instance, an IoT CO_2 sensor may emit JSON-formatted messages with a certain schema including attributes such as “timestamp”, “CO2_level”, “RSSI” (Received Signal Strenght Indicator). Each field is described with the corresponding unit of measurement and aligned with a vocabulary of properties that are relevant for the IoE;
- an *Agent* possesses a current *Role*, e.g., maintenance technician or CNC operations manager, for which a set of *Rights*, e.g. read/write, are specified. A right can hold on a specific system, on an entire smart object or on all objects within an environment;
- an Agent can have *Preference*s on specific properties, e.g., employees may have personal preferences on temperature and humidity to ensure comfort, while a smart ventilator may specify a preference on the level of CO_2 in the environment.

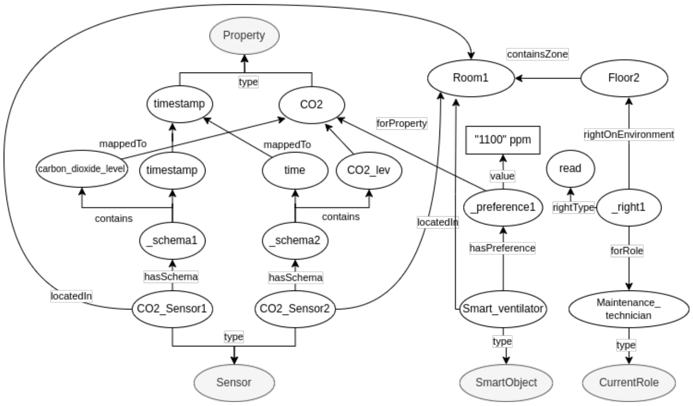

Fig. 1. Excerpt of the KG for the case study. Classes are represented in gray (namespaces are omitted).

To support data gathering, monitoring and accessing operations, also operational metadata are represented for devices producing data streams. Among them, the name of the device’s data stream (called “topic” in the following) and information on the proper system where the stream is to be persistently stored (e.g., time-series database, relational database, file).

Figure 1 shows an excerpt of the KG for the case study, with two CO_2 sensors deployed in a room. The schema of the messages produced by the sensors are depicted together with alignment with shared concepts. In the same location, the preference of a smart ventilator for a level of CO_2 is reported. Finally, employees with the current role of maintenance technician are entrusted the right to read sensor values for all devices in the room’s floor.

B. Architecture

The framework architecture is designed with multiple independent layers that collaborate with each other, enabling dynamic and flexible extension. Technical interoperability is facilitated by standardized communication protocols and data formats, while semantic interoperability relies on the Knowledge Graph, enabling seamless integration of devices and flexible monitoring. To effectively manage expanding workloads while maintaining optimal performance, the framework exploits scalable stream management modules. A key aspect of this framework is the treatment of each device or data source as a producer of data streams. This approach standardizes data management by ensuring that all data is handled in a uniform manner. This stream-based model simplifies the integration of new devices and data sources into the system, as they are all processed and managed consistently.

The platform architecture is sketched in Figure 2 and briefly described in the following:

- Data collection consists in the collection of data streams generated by sensors, including wearable devices, smart objects and other IT (sub)systems, e.g., Business Process

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[2] The full specification of the ontology is available at https://w3id.org/semioe.

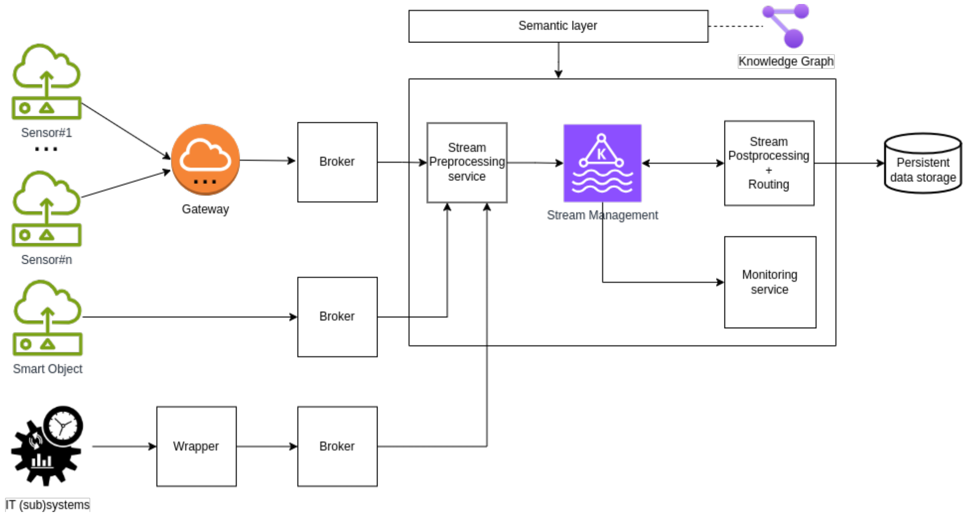

Fig. 2. Data gathering and monitoring architecture

Management systems, location detection frameworks, Identity and Access Management Systems. Sensors and smart objects can communicate their data to specific gateways, i.e. devices which receive data from multiple sources over the chosen communication protocol, and aggregate them before forwarding the integrated stream to a broker. For instance, carbon dioxide (CO2) sensors may utilize the BACnet/IP protocol and send data about air pollution in XML format, while temperature and humidity sensors may employ the MQTT protocol and transmit data in JSON format. The gateway then delivers data to a MQTT broker that manages such streams in corresponding "topics", following a publisher/subscriber messaging model where clients can subscribe to topics to receive relevant messages. In IoT applications, topics are typically structured hierarchically and encode the context of a device, allowing for logical organization and categorization of data, e.g. `room1/CO2_sensor2/CO2_lev`.

Alternative architectures can be deployed, depending on the capabilities and the interface of the devices, such as direct communication with the broker. In some cases, if the smart device is equipped with sufficient computational power and intelligence, data can be directly processed on the edge. This ensures that sensitive information, e.g. health metrics and personal activity logs produced by wearable devices, remains local to the device, preventing it from being transmitted to centralized messaging brokers. Local processing can also lead to faster response times and more efficient real-time decision-making, leveraging the capabilities of smart objects to provide a more efficient and responsive system.

As for IT subsystems, specific wrappers can be devised, which generate a stream of messages starting from events in the corresponding subsystem (e.g., the creation of a new task in a calendar or the execution of an activity in a BPM system). Such stream data, in order to guarantee a uniform management, are then published in a local broker.

- Stream preprocessing is performed by a set of services collectively acting as a bridge which consumes data streams from the brokers and performs the required transformations before publishing the streams as topics in the stream management system. Transformations can include stream merging, stream splitting, filtering out irrelevant information from messages, based on the device metadata in the KG, or performing data transformation such as decompression, decryption, scaling, normalization.
- Stream management is operated through a Kafka[3] cluster, an open-source distributed streaming platform designed for real-time data processing at scale. It provides a publish-subscribe messaging model, where data is organized into topics and divided into partitions for parallel processing.
- The Stream postprocessing service allows to apply rules before routing the stream to the proper database management system, according to the device metadata in the KG. Rules include data filtering to reduce the size of stored data, or stream transformation and republishing as a new stream in Kafka.
- Stream monitoring services allow to dynamically consume data for downstream applications, such as real-time analytics, mobile user applications, or Event-Condition-Action frameworks. It also integrates with external framework components to implement data governance policies and access controls to ensure data security, privacy, and compliance with regulatory requirements.
- Semantic layer: it is responsible of providing platform services access to the Knowledge Graph. By retrieving information on metadata of data sources, including the data schema and the sensor location, it is possible to support

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[3] https://kafka.apache.org/

dynamic stream processing and personalized monitoring, as discussed in next Section.

IV. DATA STREAM MONITORING

The continuous and rapid generation of data from smart sensors requires real-time data analysis mechanisms for retrieving information in timely decision-making context. The monitoring service supports different approaches (basic and semantically supported) to continuous tracking, observing, and analyzing data as it flows in real-time from various sources, by subscribing to specific topics. Basic monitoring is based on direct subscription to topics, by referring to conventions for their naming, e.g. `room/sensor_id/measure_type`. Besides these simple yet powerful conventions, however, this approach is purely syntactical. As such, accomodating changes or expansions is not always straightforward, e.g., when a value is renamed, a new dimension is added or the hierarchical structure of a dimension (e.g., room/floor/building for the location) is refined. As the topic structure becomes more complex, it can become harder to maintain consistency across topic names, leading to potential errors in topic subscriptions and message handling. Through the semantic layer, the platform extends the classical approach for monitoring to a more advanced semantic data stream monitoring, which decouples the topic naming with the semantics of the stream. In this approach, requests are formulated as a conjunctive set of constraints, where each constraint refer to a class and corresponding instances in the KG. The service uses these constraints to compose a SPARQL query that is executed on the Knowledge Graph, possibly exploiting logical reasoning to infer additional knowledge. Additionally, an aggregation function can be expressed, e.g. average or sum, and a time window, e.g. 5 minutes, which allows to aggregate results accordingly. To make an example, the constraints $[\{Property : [CO2]\}, \{Site : [room1]\}]$ aim (1) to identify all devices satisfying the constraints in the Knowledge Graph, i.e. *CO2_sensor1* and *CO2_sensor2* which provide a *CO2* measurement and are located in *room1*, their data schema and topic names. Then, (2) corresponding subscriptions to such topics are done. Finally, (3) the content of the incoming messages are interpreted according to the schema of the devices, translated to the corresponding shared terminology (e.g., *CO2* instead of *CO2_lev*) and are returned to the client, possibly applying post-processing rules, e.g. averaging or windowing. The approach can serve both employees for real-time monitoring and smart objects in performing automated actions, e.g., the smart ventilator monitors the average CO_2 in the room where it is located, to automatically apply ventilation if it exceeds the preference value of 1100ppm.

Both basic and semantically supported approaches are subject to an authentication mechanism, that grants access to data streams only to authenticated *Agents* within the organization, whether they are Smart Objects or employees. The authentication phase is crucial as it facilitates the implementation of a role-based access control: the constraints in the query ensure that the KG returns outputs specifically tailored to the *Agent*'s current profile within the area they are located. Let us consider the case example scenario where an *Agent* possesses a current role, e.g. as a maintenance of the ventilation system, and is responsible for monitoring the temperature values in the second floor of the building. As depicted in Figure 1, the role grants read permissions on the environment corresponding to "Floor2", and this logically extends to all sensors (e.g., $CO1\_sensor$ and $CO2\_sensor$) installed in every room (e.g., $room1$) located on the second floor. This information can be automatically derived from the Knowledge Graph by performing inference through the use of a logical reasoner during querying.

V. CONCLUSION

This paper introduced an architecture for achieving semantic interoperability in Internet of Everything (IoE) environments, utilizing an Enterprise Knowledge Graph representing and interconnecting information on smart objects, people, organization locations, preferences and right access policies. The proposed approach addresses key challenges in data integration, real-time processing, and user interaction in industrial IoE scenarios. In particular, scalability issues can arise when managing large-scale data streams, and potentially impact the responsiveness of the system, affecting its usability in time-sensitive applications. The proposed architecture aims to address this issue through a layered structure including modular components and technologies such as Apache Kafka. This acts as a high-throughput, low-latency platform for handling real-time data feeds, enabling the system to scale horizontally and distribute the data load. Furthermore, it's important to note that the scalability issue is mitigated by the fact that the Knowledge Graph primarily stores metadata about the devices. As a result, its size does not directly correlate with the increase in the volume of raw data. This approach ensures that the Knowledge Graph remains efficient and capable of handling extensive information without compromising performance. Additionally, implementing effective privacy measures and ensuring data security are crucial but challenging, especially when dealing with sensitive information. To this end, our architecture leverages edge processing, where sensitive information remains local to the device, significantly reducing the risk of data breaches and unauthorized access. This approach ensures that only aggregated data is transmitted, preserving the privacy of the users. Moreover, anomaly detection techniques such as behavioral fingerprinting, can play a vital role in enhancing data security, allowing for the identification of irregular patterns and potential threats by analyzing the behavior of devices and network traffic. By implementing a scalable, modular framework with edge processing and advanced anomaly detection techniques, the system efficiency and security can both be enhanced.

This research paves the way for future developments within the HOMEY project, which aims to develop an industrial IoE framework enabling users and machines in cooperating and exchanging relevant information in a trusted, efficient and effective way. In particular, besides the full implementation and testing of the data gathering system, the goal of personalized data access will require the definition of proper methods.

Among them, to guarantee uniform data access over disparate data sources, ontology-based data access approaches will be investigated, along with tools to guarantee an immersive exploration of the IoE data ecosystem using zero-touch interfaces and Augmented Reality.

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