An Approach for Context-Aware Cyber-Physical Automation Systems

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Abstract: Future automation systems, operating under increasing dynamic conditions need to be equipped with methods to enhance their adaptability accordingly. Context-aware systems model and apply contextual parameters influencing the interpretation of situations to adapt their operation accordingly. Designing context-aware automation systems requires methods to acquire and process heterogeneous and distributed data in a dynamic and continuous manner. In this contribution, a methodology for processing multimodal data in a flexible and reusable context-model is demonstrated, using concepts of data aggregation and integration, semantic labeling and graph modeling. Based on this approach, the use case of a context-aware medication assistance system is subsequently presented.

Keywords: automation systems, cyber-physical systems, context-awareness, medication assistance, graph modeling, pill dispenser

1. INTRODUCTION

Motivated by the fusion of information and automation technologies as well as the increased networking and data acquisition capabilities within the industrial domain, new approaches for monitoring and optimizing systems are emerging. Automation systems are increasingly becoming networked hardware- and software-based systems, dynamically collaborating and interacting with variable systems as well as operating in varying, sometimes previously unknown conditions. (Monostori et al., 2016) Surrounding contextual parameters influence the system's operation. Thus, considering changing contextual parameters and enhancing automation systems with context-awareness can lead to a more efficient adaptability (Caesar et al., 2019) as well as a better understanding of the system. With the benefit of adapting to externally changing conditions by adjusting functionalities and services, the design of context-aware systems has been increasingly set as a research focus for the past three decades (Knappmeyer 2013). However, design approaches within the automation, especially the industrial automation domain remain scarce and tend to be application-oriented, which aligns with the additional challenge of lacking a standardized definition and modelling schema for context as well as context-awareness. Generally, context-awareness describes the ability of a system to model and incorporate contextual information and adapt a system's functionality accordingly. (Dey, 2001, Perera, 2014). As automation systems are increasingly digitally represented in the cyber world and become networked cyber-physical systems (CPS), a potential of acquiring and continuously modelling context using cyber resources for a more efficient operation is possible. Ongoing research on CPS suggests intensifying research activities towards a stronger cyber-representation for CPS by the generation and use of digital models to improve planning, control and monitoring during the system's operational phase. Modelling influencing external parameters with regard to their influence on the system operation is essential and can provide a better understanding of the CPS for improved operation and decision-making. For component fault diagnosis, for example, often an underlying reason can be attributed to the historical operational context of the system. For decision making use cases related to reconfiguration and optimized resource use, considering further and present context parameters outside of the system's boundaries presents a further advantage. Thus, focusing on methods for enabling context-awareness aligns with the ongoing research interest for highly adaptable and autonomous systems. A holistic, system-centric approach for modelling and using context during runtime is therefore needed.

Generally, context is characterized as **multimodal** and **dynamic**. Although the potential of modelling and considering contextual data is promising, it remains a challenge to acquire, aggregate, model and manage context when considering its heterogeneity and dynamic characteristics.

The Internet of Things (IoT) has enabled data acquisition from remote and embedded data sources such as sensors. Furthermore, resources to process large amount of streaming data through remote servers and services give potential to a more efficient processing of data and gaining more insight about systems (Ding, Jing, Yan, & Yang, 2019). With these advancements, the key challenge remains in linking and applying acquired data in purposeful functions. The acquisition, integration and accumulation of context data is necessary. To realize a holistic approach for future automation systems, the applicability of the modelled context should be scalable for a variety of services. Which leads to the research necessity of a concept for context-aware cyber-physical systems with a focus on data acquisition, system-centric context modelling and scalable usability.

In this contribution, an approach for defining and acquiring context data around a CPS using an intelligent framework for context-awareness is demonstrated, enabling context-adaptive control. A context modelling approach based on a dynamic metamodel is presented. The concept is demonstrated by an automated medication assistance system, namely, a networked and user-centred pill dispenser. The rest of this paper is structured as follows: Chapter two addresses related fundamentals to the definition of cyber-physical automation systems, context-awareness as well as basic concepts of IoT-based data fusion. In chapter three, the proposed concept for a flexible context-middleware for CPS is described, followed by a use case of a medication assistance system. To conclude the contribution, a summary and outlook are last addressed.

2. CONTEXT-AWARENESS FOR CYBER-PHYSICAL SYSTEMS

This chapter addresses related concepts to cyber-physical systems, data fusion as well as the design of context-aware systems, concluding with requirements and design considerations for CPS data acquisition and context processing.

2.1 Cyber-physical automation systems

Cyber-physical systems (CPS) are collaborative, dynamic systems consisting of sensors and actuators, which are connected to computational entities that are capable of learning by acquiring and processing information to infer action. The physical CPS environment encompasses the system under control with its sensors and actuators, whereas the cyber world includes the computational resources and digital artefacts as well as services enabling control/decision-making, monitoring, storage, and analysis. (Jazdi, 2014). CPS are increasingly applied within the industrial, medical as well as ubiquitous computing domain.

As CPS are equipped with computational resources enabling learning, they can interpret and process context into meaningful knowledge. The ability to gain knowledge from context becomes essential for CPS in order to enhance that intelligence. (Sahlab, Jazdi & Weyrich, 2020)

2.2 Context-aware systems

Linguistically, context refers to additionally present implicit information, which contribute to a better interpretation or understanding of an event or situation. In the domain of computer science and pervasive computing, context has been commonly defined as implicitly available information, which can be used to reflect the situation of an entity during its interaction with a system. This definition limits the scope of context to relevant information for specific interactions or applications (Dey, 2001). There is no consensus on a standardized definition for context, as it varies in scope and is mostly application-oriented. However, as CPS are intended to be dynamic and adaptable, a more holistic approach to dynamically define and model context at runtime is necessary. Therefore, the CPS context can be described as a set of aggregated and time-continuous data around the CPS representing flexibly connected entities sharing a conditioned goal or environment as the CPS and contributing to a better assessment of its operation. (Sahlab, Jazdi, & Weyrich, 2020)

This definition encompasses the dynamic nature of CPS as it includes the notion that the context surrounding CPS and the respective data representing it is typically time-variant as connections between entities evolve. It also limits the scope of entity as certain subjects/objects, which have the same goal or are in the same environment as the CPS. It is also important to note that something is context only if it is able to contribute some meaningful knowledge about the system.

Context-awareness is the processing of contextual information and the ability to react accordingly and optimize the system's behaviour. Hence, context-aware systems are defined as systems that are able to collect and use context and behave dynamically based on it, which is referred to as context-adaptive control. (Knappmeyer 2013) This processing and execution can either be in an automatic or semi-automatic manner. (Perera, Zaslavsky, Christen, & Georgakopoulos, 2014). Applications of context-aware systems in the industrial domain include context-sensitive reconfiguration (Caesar et al., 2019), as well as requirement engineering (Tenbergen, Daun, Aluko Obe, & Brings, 2018).

2.3 Requirements for context-aware cyber-physical automation systems

Context has the characteristics of being, dynamic, acquirable from different sources, thus heterogeneous and as a result, uncertain and fuzzy. A context-aware system needs to be equipped with capabilities to dynamically acquire heterogeneous context data. Furthermore, a unified model representing the collective context is a pre-requisite for an efficient application of context. Reasoning and analysing the context model is a further requirement for inferring knowledge. Usually, a context-aware system consists of a context acquisition, context-modelling and reasoning component, which in sum comprise the context lifecycle. In the following sections, requirements for designing context-aware cyber-physical automation systems are listed, focusing on context data acquisition and their modelling, reasoning as well as architectural design of necessary framework aspects.

- **Heterogeneous data acquisition**: Data fusion describes mechanisms for collecting and aggregating heterogeneous data to improve decision making and analysis based on multimodal information. In light of IoT, the distribution of data sources as well as the uncertainty and dynamic handling of data represent challenges. Knowledge-based data aggregation and integration approaches rely on defining a concept for fusing data and applying AI-based methods (e. g. intelligent data fusion, machine learning, machine perception) for a unified and consistent knowledge representation. Context has the characteristic of multimodality as it is acquired from different sources, which collectively represent the system's current operational circumstances. (Ding, Jing, Yan,

& Yang, 2019) Therefore, remote data acquisition, pre-processing and uniform integration are essential for context-aware CPS. Mapping relevant different sources to context at runtime as well as managing and validating them are further requirements.

- **Dynamic context modelling**: The central component for applying context is context-modelling. Modelling approach should consider the complexity and adaptability requirements of the system. An important requirement for the model is to focus not solely on the individual elements, but also how they relate and connect to each other. Therefore, proper approaches for describing relations are necessary. Lastly, modelling context for CPS needs to consider emergence and evolvement of new conditions at runtime, so efficient methods for managing and updating the model at runtime are necessary. (Li, Eckert, Martinez, & Rubio, 2015). Ontologies and graph-based context modelling approaches are prominent as they focus on relations between context elements and consider complexity.

- **Automated context reasoning**: As the acquired and modelled context has a certain degree of uncertainty, reasoning approaches need to address this aspect by providing tools for consistency checks. For a pre-defined system's context scope, reasoning over pre-defined rules is a classical and prominent approach, other approaches include probabilistic, ontological (description logic-based) or hybrid approaches. As for newly arising context at runtime, reasoning becomes challenging and requires increased use of automated learning. (Hasanov, 2019)

- **Decentralized architecture**: To realize a context-aware system on an architectural level, centralized, decentralized as well as middleware-based approaches exist. Decentralized approaches enable the application of remotely allocated computing sources and IoT-based data acquisition. Middleware-based approaches are advantageous as they hide the complexity of heterogeneous data acquisition and context processing and separate the data acquisition layer from the context lifecycle (Perera, Zaslavsky, Christen, & Georgakopoulos, 2014). Furthermore, this architectural approach enables scalable reusability of the context-model by different applications and services within an application layer by standardized interfaces. In CPS, this could be realized by introducing a context layer between the physical and cyber environment (network layer and application layer) of the CPS.

2.4 Proposed approach

Based on the derived requirements in *2.3*, an approach for designing a context-aware cyber-physical automation system is proposed. The approach considers heterogeneous data acquisition via an IoT integration platform and models context using semantic labelling and graph-based approaches to highlight the dynamic relations of context entities. The context graph is managed and stored within a graph-database. A middleware design approach enables a standardized and scalable access to the managed context-model via variable applications, which consider relevant contextual elements to adapt and control the system. In the following chapter, a detailed description of the system with a focus on deriving and acquiring the relevant context at runtime.

3. A FRAMEWORK FOR CONTEXT-AWARE CYBER-PHYSICAL AUTOMATION SYSTEMS

In this chapter, the concept and architecture of the context-aware cyber-physical automation system are described with a special focus on context acquisition. The context metamodeling and modelling approach as well as the context application are briefly described.

3.1 Identification of context scope

In order to determine the context scope for an automation system, both a system assessment as well as an analysis of the relevant context must be performed and put in relation to each other. The following Fig.1 illustrates this process.

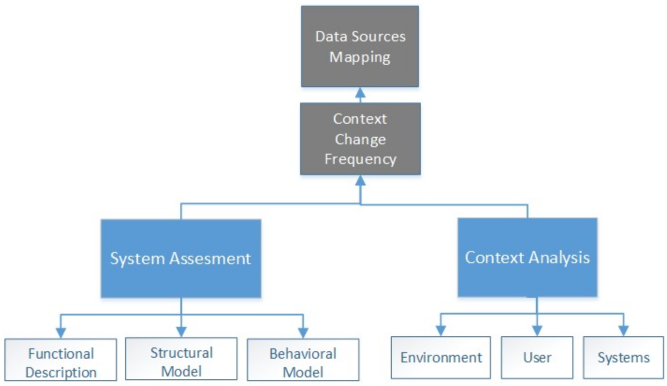

Fig. 1: Defining the context scope in relationship with a system assessment

First, a structured system assessment using available digital artefacts is conducted, which considers its components, functionalities and behaviour and derives its goals. An automation system can have multiple operation modes depending on its control program and function scope. Each mode can be encapsulated in sub-model entities within the functional description. The result of the system assessment is then represented applying features of the Unified Modeling Langauge. The multi-staged models show the inter-relations between the system's components with its functionality and behaviour at runtime. In the second part, context analysis is conducted. Context information encompass parameters, which are outside of the system's boundaries and present during its operation. As the presented approach aims at modelling context at runtime while considering a dynamic variation of its scope, so rather than pre-defined context information, a categorization-based top down approach is followed. The main three categories are operational environment, user and collaborating systems. The operational environment includes the physical parameters such as temperature and humidity as well as spatio-temporal data. The category user includes necessary and implicit user data, which might affect the interaction of the user with the system. Depending on the functionality scope, user data can be relevant solely for the human-machine interaction or for the system operation in case of automated assistance systems. In the following step, a mapping of available data sources to the listed categories takes place. The last step is determining the frequency of context change to decide on the frequency of data acquisition. Here, two design features can be applied, a time-based and an event-based approach. The time-based approach is a systematic approach using cyclic communication, where a time frequency for context assessment is chosen, depending on the system's operation, e.g. on hourly or daily basis. The event-based context update occurs every time an external context change occurs related to collaborating systems or a change of user data entered in the system. After this initial system analysis, the process for context modelling is initiated, which will be described in the following section.

3.2 General framework overview

Fig. 2 depicts the architectural approach for dynamic context modelling for CPS.

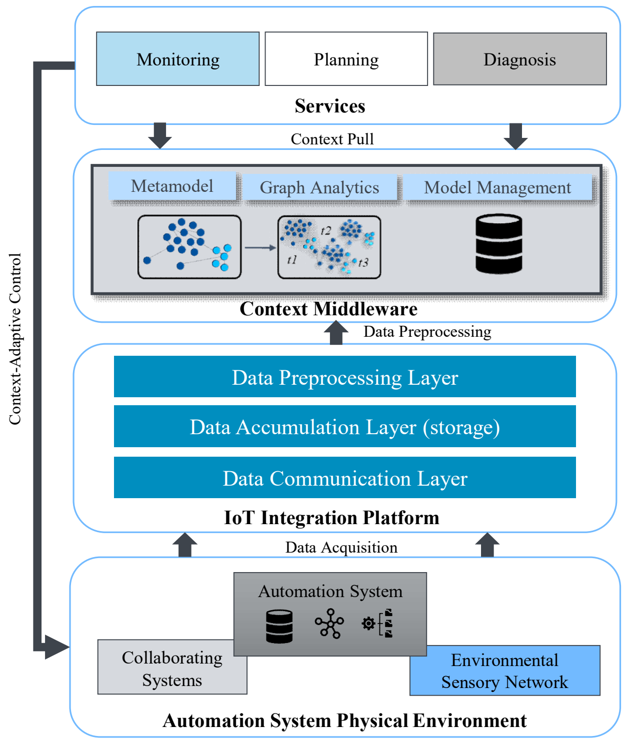

Fig. 2 Conceptual framework for a CPS context middleware

A middleware-based approach for context modelling is chosen, separating data acquisition, context modelling as well as its application to achieve an overall system flexibility and extendibility, especially for the acquisition of heterogeneous and dynamic data. Here we highlight on embedding the context lifecycle within the middleware and its scalable usage. Within the physical environment, the modelled automation system operates with external contextual data entities present. Identified and mapped data sources are acquired and pre-processed by an IoT integration platform. The context middleware requests the aggregated data based on the determined context-changing frequency and creates an instance of the context model based on a metamodel, which is stored and managed within the middleware. The application layer accesses the context middleware to use context as a service and pull application-specific context model entities as a sub-model from the managed context model instances. The result of the context-based application logic transforms as adapted control signal back to the automation system.

3.3 Approach for heterogeneous data acquisition

As context is aggregated from different sources, heterogeneous data acquisition via the IoT integration platform is essential for realizing context-aware automation systems. In this section, the process of data acquisition based on the requirements for modelling and processing context is presented. Based on the initial system analysis described in 3.1, relevant data sources for context modelling are connected to an IoT integration platform. Each connected data source may vary in its data acquisition method. The data communication layer is responsible for connecting to different devices and data sources via supported communication protocols, which are embedded in the driver layer of an IoT integration platform. Supported communication protocols such as MQTT, TCP/IP as well as BLE for closely allocated sources can therefore be considered. Generally, there are several known and open source IoT platform with built-in modules and a variety of widely used supported communication protocols, especially in the medical cyber-physical and home automation domain. For other industrial applications, OPC UA is a further widely used protocol. Besides different communication protocols, each data source varies in its data sampling frequency, which can be collectively adjusted according to the set frequency for acquiring the context state of a CPS. For static data such as structural components of the system or static settings, a pre-defined acquisition frequency can be set. For environmental sensors, such as temperature sensors, sensor readings can be set according to the defined context frequency change based on the system's behaviour and functions. Data sources can change during runtime, so the IoT integration platform manages connected data sources in a list and enables a simplified addition or removal of a data source, which can either be manual or automatic.

Sensor readings are sometimes subject to error, which is why a data pre-processing module checks the validity of the acquired reading using a simplified Kalman filter to compare the expected and estimated value with the actual value. Outlier detection mechanisms can also be applied to sensor readings with the benefit of a co-occurrence analysis. For example, outlier value for temperature readings can be determined in a contextual manner by observing the expected, time-based co-occurring humidity values to determine whether an anomaly due to a false sensor reading present or not.

The next step is data accumulation, i.e. the preliminary storing of acquired data within a relational database, where data is stored and structured according to pre-defined context categories (system, environment, user, and collaborating systems). The data pre-processing layer addresses the categorical labelling of data and the use of uniform exchange formats for context modelling by the middleware. For this reason, a JSON schema denoting context categories and subcategories as well as data type, unit and value is created.

3.4 Graph-based context modelling

The context middleware acquires the pre-processed and uniformly represented heterogeneous data and process it based on a defined metamodel, where the context categories and subcategories are represented. To enable a flexible extension of the metamodel, labelled property graphs have been chosen as a modelling approach. Graphs are capable of depicting relationships between context elements in a human and machine-readable fashion via nodes and edges, so the modelling process is more intuitive to understand. This modelling approach depicts relationships between context and the state of the system, so that uncertainties can also be taken into account as factors that affect the system state. Labelled property graphs have a further advantage compared with ontologies using RDFs as they enable the use of graph-centric algorithms to overcome uncertainties in the context model. Using the metamodel, which is created and updated based on mapped categories and data sources from the IoT integration platform, context model instances are created as nodes and labelled as well as weighted edges. The context middleware analyses time-variant context instances using graph-centric algorithms, which denote the most influential node. Versioned context model instances are stored in a graph database.

3.5 Context application

The last stage of the framework describes the application-based context model access. Here, the entry point to the graph traversal can be based either on a functional or structural starting point, based on which the respective context model, meaning the relations to this focus point are delivered. Furthermore, context can be requested in a specific time-range. A template of queries using the graph query language cypher have been designed accordingly. The derived knowledge about the CPS context is intended to provide decision support to adjust control signals of the CPS by adjusting certain control parameters in the control code.

4. USE CASE: CONTEXT-ADAPTIVE MEDICATION ASSISTANCE SYSTEM

Medical cyber-physical automation systems are gaining importance in light of the demographic change and the need for efficient methods to sustain health while preserving the autonomy of an ageing population. Using networked CPS and AI-based approaches is a promising solution for user-adaptive assistance. Personal medication management is an area requiring assistance to enable effective medication, especially for managing co-occurring chronic diseases. An automated medication assistance system has been developed as a cyber-physical system to assist elderly patients with the medication process starting from ordering, filling to dispensing pills to overall information managing.

The CPS shown on Figure 3 consists of sensors and actuators to detect medication intake as well as set audio-visual alarms dispense pills automatically. The system is connected to a smartphone application and a mobile medication unit. Furthermore, networking abilities are implemented to enable information retrieval by different stakeholders, for example for updating the medication plan or requesting medication intake times. The cyber-physical automation system as is presents improvement potential when becoming context-aware to the system's as well as the user's shared context. Therefore, a system and user-centric context model has been created to capture the time-variant and joined context of the assisted user and system.

A system assessment yielded a structural description including sensors, actuators as well as the computing and information storing units. The following functional description denoted the triggering of alarms, the medication dispensing mechanism as well as the pill fall detection. Information storage and update as well as information exchange and synchronization were further use cases.

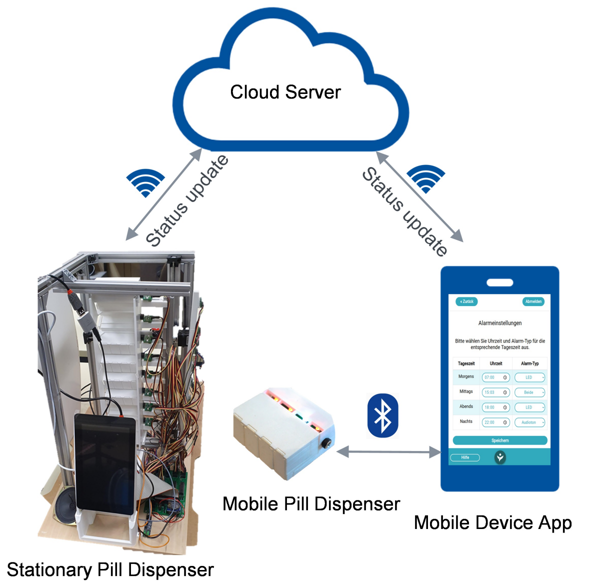

Fig. 3: Automated and networked Pill Dispenser

Contextual elements relevant to the system as well as the user were analysed. Environmental parameters included time reference around alarm times, location, temperature and humidity, as they are relevant to the storing and dispensing of medication. The user context included the activity profile and vitals during medication intake.

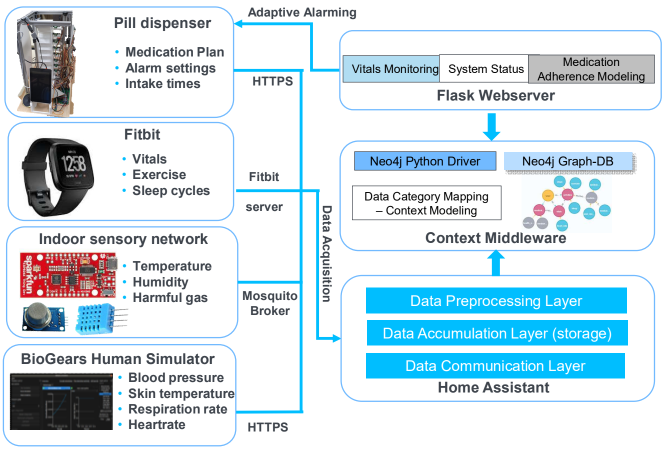

Fig. 4: Context-aware medication assistance system

The defined categories were mapped to data sources as depicted on Fig. 4. The IoT integration platform home.io was hosted on a Raspberry Pi and InfluxDB was used to accumulate acquired and filtered data. As for the context middleware, Neo4j was used for storing the metamodel and context model instances using python drivers. The application layer was developed using a python based local webserver. For context-adaptive control, three use cases were realized. The first use case addressed an iterative evaluation of alarm setting and alarm intake times and a concluded suggestion for updating the alarm setting as an average to actual pill intake time. The second use case considered was user-centric and realized context-based vitals monitoring, where the heart rate was depicted in relation to the activity and medication times. The third conceptual use case considered predicting a possible pill entanglement by monitoring the environment's temperature and humidity values. Access to the context model via applications was governed by role-based control and standard TCP/IP data encryption was applied for data exchange.

5. CONCLUSIONS AND OUTLOOK

In this contribution, design aspects for developing context-aware cyber-physical automation systems were addressed, focusing on data acquisition and aggregation for context modelling. After the proposal of a suitable CPS context definition, requirements for the design of a context-aware cyber-physical automation system were derived, addressing heterogeneous data acquisition, dynamic modelling and automated context reasoning approaches. Based on the investigated requirements, a framework for a middleware-based context-aware CPS was subsequently demonstrated including data acquisition, graph-based context metamodeling as well as a service interface. The concept was further demonstrated by use cases for a context-aware automated and networked pill dispenser, which included adaptive alarming and context-aware vitals monitoring. Future work includes an in-depth analysis for handling context uncertainty as well as automatic approaches for selectively connecting data sources, relevant to dynamic context modelling.

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