Towards a Knowledge-Augmented Socio-Technical Assistance System for Product Engineering

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***Abstract*—Digital tools for handling the whole product engineering phase are getting more and more important in the context of Industry 4.0 and an increasing product variety. However, especially in small and medium-sized enterprises, a lot of information about product development and production is stored in different documents or isolated data silos. A promising way to arrive at a solution is to model data and knowledge with ontologies and enrich it with context information. This paper presents a concept and a showcase implementation of a company-internal and personalized assistance system for an end-to-end digital product engineering process. We combine a generic and cost-efficient human assistance solution focusing on social aspects and a company-wide knowledge graph to create a seamless and highly integrated data structure that assists many stakeholders in the product engineering process, from product designers to assembly workers. As a result, more complex products can be handled and the product engineering process can be accelerated.**

I. INTRODUCTION

The need for automation is present at all levels of product engineering. Due to individual developments and the heterogeneity of solutions in small and medium-sized enterprises (SMEs), intradepartmental structures are grown. During the product lifecycle, data is often gathered in an unstructured way. It is stored and processed via various systems, either on paper or in software tools such as MS Excel or databases. This diversity leads to a multitude of factors that influence the product engineering process. A holistic representation and understanding of all aspects and their relations is very time-consuming. Dependencies in the event of parameter changes cannot always be fully traced. For instance, changes to product dimensions affect tool sizes, suitability of assembly cells, and package sizes. These uncertainties require coordination and knowledge transfer between different departments.

Specific expertise on manufacturing processes often exists only in the heads of individual experts and, therefore, is not formally specified or digitally accessible. Related data and information cannot be automatically processed, e.g., for continuous digital documentation or compliance checks regarding customer needs. As a result, optimization potential often remains unrecognized. To address these challenges, a uniform and integrative digital assistance system is necessary.

The topic of digital worker assistance systems is perceived as highly relevant in the context of Work 4.0 [1]. The German engineering federation VDMA founded a working group "Handmontage wird digital" (manual assembly goes digital), in which industry and academia address this topic [2].

Despite high relevance and first commercial implementations, these systems have not yet found widespread use. The VDMA working group has identified reliability, robustness, usability, and the promotion of acceptance among employees as central research areas of digitally supported manual assembly that need to be advanced.

This paper focuses on a so-called Socio-Technical Assistance System (STAS) for the product engineering process, including the whole product lifecycle from design to manufacturing and logistics. The approach introduces a generic, transferable, and expandable solution to assist many different stakeholders, like product designers or assembly workers. The system is based on different abstraction layers integrating machine learning for computer vision, semantic representations of different knowledge entities, and their interrelations. An ontology-based semantic knowledge representation enables linking of knowledge from various domains at different hierarchically-defined levels of granularity. Products, manufacturing processes, and resources can be semantically modeled and linked with customer requirements, compliance criteria, and associated engineering activities. Furthermore, computer vision is used to guide, monitor, and verify performed production steps of assembly workers.

II. RELATED WORK

Semantic description languages, e.g., based on the Web Ontology Language (OWL), have been widely investigated in product engineering in recent years. For product engineering, different methods are given in the literature such as the Advanced Product Quality Planning (APQP) approach. APQP is a structured method for defining and establishing the necessary steps to ensure that a product is planned, designed, manufactured, and launched effectively according to customer needs. In [3], ontologies are integrated into the APQP process to effectively combine and reuse the relevant and actionable knowledge from both the design and manufacturing process domains. Similarly, [4] introduces a part-focused manufacturing process ontology covering the gaps from product specifications to manufacturing processes, where the specific process requirements can be selected based on desired features and attributes. Further related applications for ontologies are geometric specification of CAD models, e.g., using an ontological boundary representation (OntoBREP) [5], as well as the description of skills [6] and capabilities [7] of workcell resources.

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In our preliminary work on digital worker assistance, a gesture recognition method is introduced [8] and integrated into an assistance system with self-learning capabilities [9]. There are also a number of papers investigating the fundamental topic of intelligent assistance systems with a focus on two central issues: firstly, the support of the activity by a cognitive system providing context-sensitive information [10], [11] and secondly, gamification features to maintain concentration and long-term working power [12], [13]. While traditional assistance systems are usually optimized for individual processes in an elaborate manner, ontology-based methods focus on the automatic generation of dynamic assistive instructions from existing enterprise data, e.g., from the context-level information of users, tasks, environments, and information devices [14], or from the template of a product family [15].

In this work, semantic information models on products, processes, and assembly workcells are combined to endow the digital assistance system with the ability to support throughout the product lifecycle, including verifying customer requirements, generating work instructions, and monitoring performed tasks through automatic labeling and interpretation of sensor-based perceptions in the workcells.

III. CONCEPT

The proposed concept aims at developing an assistance system for product engineers and assembly workers covering the product lifecycle with a complete, seamless process chain. Supporting digital transformation at several company levels enables the sustainable introduction of end-to-end digital process management, which provides the grounds for the successful implementation of an AI-based assistance system. This is achieved through the development of semantic information models and their integration into a system architecture that enables knowledge-based engineering. The semantic information models are interpreted logically, e.g., for traceability along the value chain or the synthesis of work instructions.

Assembly workers are guided by the assistance system, which further documents and verifies work results. The system is able to assist with onboarding measures to lower the impact of personnel fluctuation on productivity. The focus here is particularly on the worker, who has to cope with increasingly complex manufacturing processes. However, the involvement of other people throughout the entire product engineering process is also crucial to ensure that all relevant information is captured and considered.

Fig. 1 depicts an overview of the proposed concept of a knowledge-augmented STAS that supports the product engineering process from the design of the product and its production process to the actual assembly. Particular components of the overall system are further described in the following.

A. Semantic Models and Knowledge Base

Ontology-based semantic description languages are designed to represent relevant knowledge regarding the manufacturing process, the product that is designed and assembled, and the resources that are involved in these activities. This includes the modeling of production steps, their logical and temporal dependencies, manufacturing parameters, and derived requirements that machines and workers and their tools have to meet. For the formal modeling of mechanical products, the CAD ontology OntoBREP [5] is used to represent geometric information on a semantic level. Additional annotations regarding product properties and APQP-guided product development can therefore be applied to any geometric subset of the OntoBREP representation. For instance, the process description can directly refer to individual points, curves, or surfaces of the product's geometry model and thus represent a better understanding of the relationships between customer requirements, production processes, and the product itself. Furthermore, the parameterization of subtasks of the manufacturing processes or product characteristics can be – to some extent – automatically derived.

Whereas geometry models can be automatically converted from industry formats (e.g., STEP), processes often have to be specified via GUIs that act as a frontend to the semantic models. Process models may be (partially) generated, if relevant information is available in company data sources [16].

Individual human capabilities are explicitly modeled, covering generic best practices, e.g., suggested load limits and qualification levels. Tool-induced capability extensions are captured and derived in an automated way. In addition, worker capability models may be augmented with experience models to enable the assistance system to optimally match the users' needs and skills. Technical resources, i.e., the components of the assistance system, are semantically described and used in a capability matching process to determine if a workcell configuration is compatible with a given assembly task.

The introduced description languages provide the vocabulary to describe relevant entities and their relationships in the application domain. For specific use cases, these concepts must be instantiated. The interlinked semantic instance models form a knowledge graph that is persistently stored in a knowledge base. This knowledge base provides means of automatic reasoning via logical inference and data manipulation with the SPARQL query language. Consequently, many explicit and implicit aspects can be considered for decision-making in general, and adapting the communication modalities and communication contents of the assistance system in particular.

B. Multi-Modal Human Interface

A vital component of the STAS concept is the interaction with the human worker, represented in Fig. 1 by the components in yellow. The STAS includes interfaces that process human-induced input, such as hand movement, and provide feedback on the current context to verify the production step. For guidance, the worker can request specific process and product information. The different and flexible UI boards help with problem-solving, decision-making, and planning for unsupervised workers and the managing executive. Gathered data is fed into the *Scene Perception*, *Activity Recognition*, and *Knowledge Extension* model and tagged with semantic annotations. Each model can be fine-tuned for each predefined

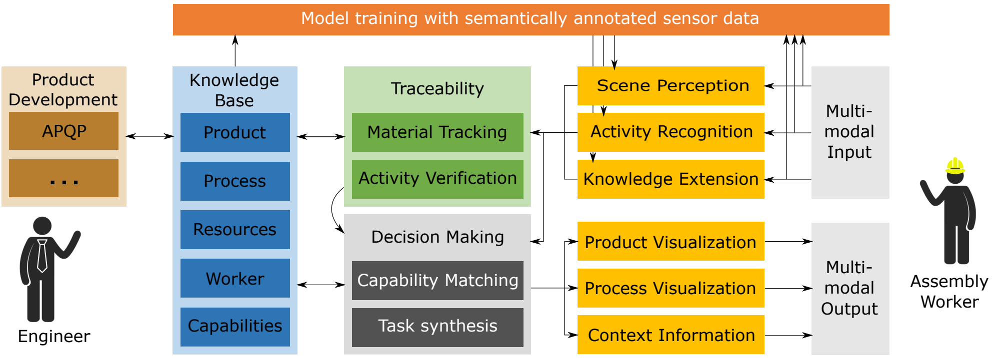

Fig. 1: Concept of a knowledge-augmented socio-technical assistance system for manufacturing companies

synthesis task stored in the knowledge base. The STAS uses different, abstracted input and output modalities to communicate with the worker.

1) Input Modalities: The input modalities are primarily designed for processing and distributing camera data to corresponding models. This setup removes the need for specialized hardware and can cover a broader range of use cases. The software-based models allow fast, flexible, and over-the-air updates and are not limited by on-device training. In addition, there is an interface for special hardware, events, and human input. Based on the image data, three main abstraction modules are implemented:

- *Scene Perception*: Localization and orientation estimation of components and tools known to be used and required within the current process. As it is impossible or not economical to use precise and complex sensor setups, not all necessary components can be detected with a satisfying probability. However, the system can request information from workers about missing or unknown components and tools, allowing for localization and further tracking throughout the assembly process.
- *Activity Recognition*: Recognition of events regarding the manufacturing process based on human interaction with the workplace. The system can follow predefined process steps from the knowledge base and react on process deviations to optimize the underlying model or give feedback to the user.
- *Knowledge Extension*: Triggering (perception) events based on user and process context. The model is trained to capture required assembly data for documentation and traceability purposes, such as further user acknowledgment or a high-resolution image for later verification.

Available information is semantically encoded, persisted, and further processed within the knowledge base by the traceability and decision-making components.

2) Output Modalities: The STAS is integrated within a company's infrastructure and can access all relevant context information to assist the worker. Available information is distinguished into product, process, and production context. At the workplace, this information is filtered by importance and automatically displayed to the worker or shown in detail on request. Generated information can be aggregated to summarize production cell states and notify production schedule deviations in real-time. Furthermore, not only can context-specific information be made available to the worker, but the concept also allows to give design feedback back to the product engineer. The feedback can be directly linked to specific geometric entities due to the ontological representation of products and associated processes.

IV. EXPERIMENTAL RESULTS

This chapter demonstrates the showcase implementation of the assistance system that guides a worker through the individual steps of an assembly process. The system aims to facilitate the transfer of formalized knowledge to the workcell and return context-specific information about its physical state. For example: 'Where is the screwdriver that satisfies specific criteria, such as torque and bit attachment?'.

The assembly process is carried out in a manual assembly cell equipped with RGB-D sensors to perform various depth- and color-based detections (see Fig. 2, left). The semantic knowledge base is utilized to load the necessary information for the assembly and contains information about all basic, individual assembly steps, the needed tools, and the effects of the individual steps. Also, the capabilities required by the manufacturing process and the ones provided by the workcell and its tools are compared. Based on the semantic process model, the worker can be instructed on which parts need to be picked, which tools need to be used, and which parts or tools (i.e., capabilities) are missing – if not present in the cell.

Initially, the tools and parts required for the assembly process are localized using the installed sensors. The user is notified if the required tools and parts are unavailable. During the assembly process, each individual assembly step requires only a specific subset of tools and parts for each step. The knowledge about the current assembly step allows to focus on interesting regions, enabling more precise 6D tracking of the individual tools. This approach enables tool states to be tracked with centimeter accuracy while robust to certain occlusions, and to be continuously checked for discrepancies. Furthermore, human hands are tracked on joint-level granularity, giving meaningful insight into what is happening and where. Fig. 2 (right) visualizes the data that is

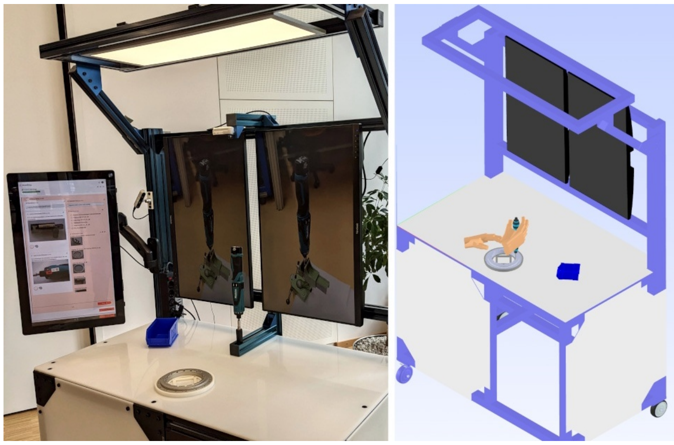

Fig. 2: Manual assembly cell with screens for showing instructions and associated context information, two RGB-D sensors to track hands and objects, assembly parts, and an electric screwdriver (left). Visualisation of tracking information semantically labeled and stored in the knowledge base (right).

recorded, stored, and automatically analyzed in the knowledge base, i.e., in this case the geometric representation of the workcell and the detected hands, tools, and parts. The figure shows a screw tightening process, where both hands and a screwdriver are precisely tracked. The assistance system can be flexibly parameterized based on the current subtask of the semantic process model. For instance, in the depicted step, the perception system detects only the hands and a screwdriver, i.e., entities that are relevant to the current task. This softens privacy issues, as no videos have to be persistently recorded, while still meeting traceability requirements.

The experimental results show that the explicit representation of context knowledge and highly integrative nature of knowledge graphs allows, on the one hand, to use the same knowledge in different product engineering stages and, on the other hand, to adapt the assistance system to different processes and human workers in a flexible way.

V. CONCLUSION

The current trend in manufacturing towards higher product complexity, variant diversity, and smaller batch sizes is characterized by a large number of different activites in the domains of product design, development, production, assembly, and quality assurance. A continuous improvement of these processes is necessary to meet the demand for increased efficiency, shortened delivery times, and verification of customer requirements. The concept of a knowledge-based STAS supports the coordination between the functional areas. It can improve both efficiency and effectiveness of manufacturing SMEs through various outcomes: Product engineering cycles can be shortened through the integrated use of information across all systems, all stages of the value chain, and their individual preparation for the respective recipient, as well as corresponding feedback loops. Errors can be prevented more reliably, and associated risks of the human factor can be reduced through the use of assistive technologies. Training and onboarding processes can be accelerated through the use of a system that promotes self-learning of employees. The scope of actions of employees can be expanded via systemically guided empowerment. As a next step, the implemented solution will be tested and verified in realistic assembly scenarios. The feedback will be used to refine the semantic models, especially the capability and experience models of workers, to increase the adaptability and flexibility of the system.

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