Using goal modeling for defining digital twins in industry automation

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Abstract

Goal modeling is commonly proposed and used for early requirements engineering, allowing easy documentation of high-level requirements and their interrelations. In recent years, goal models have often been suggested to support the definition and analysis of cyber-physical systems, also from the industry automation domain. For the future of manufacturing, digital twins play a vital role. The digital twin allows for in-depth analysis of the requirements and processes of the factory and supports action planning for new tasks. In this paper, we investigate the use of the goal-oriented requirement language (GRL) to define goal models that support the digital twin in industry automation.

Keywords

Goal Modeling, GRL, Digital Twin, Industry Automation

1. Introduction

Digital twins are virtual representations of physical systems [1]. In smart manufacturing, digital twins are used to monitor and analyze the overall state of the factory and its production processes. Therefore, the digital twin helps in runtime adaptation planning, due to new production orders or due to the identification of unforeseen events or the occurrence of errors during process execution. In industry automation, digital twins, for instance, allow monitoring production processes, calculating optimal factory allocation, or predicting manufacturing outcomes and potential defects (cf., e.g., [2, 3]).

Among others, the huge potential of digital twins is seen in supporting safety assurance at run-time, exploring problem spaces to find optimal or near optimal solutions, foster prediction of run-time properties [4, 3]. One of the primary challenges encountered with digital twins is its systematic definition, particularly considering generalization and managing large-scale operations [5, 6]. A digital twin doesn't achieve immediate perfection; it necessitates the accumulation of extensive data sets before it can autonomously make accurate predictions. This could take quite some time and these predictions also require a variety of data (positive and negative), to build the digital twin. Therefore, currently, digital twins are mostly used as research

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prototypes developed by data scientists in a trial and error approach. This is exacerbated as in the industry automation domain no strong emphasis is given to systematic software development but more to mechanical engineering aspects. To support the systematic development of digital twins in manufacturing scenarios, goal models [7, 8] might be a promising solution as it allows early definition and analysis of the system and its digital twin at moderate effort [9, 10].

This paper contributes an investigation to a) evaluate whether goal modeling can be beneficially applied to the development of digital twins for manufacturing use cases in industry automation and b) identify necessities to be taken into account for the definition of a comprehensive goal modeling approach for the specification of digital twins in industry automation use cases. Thus, this research is part of a larger research agenda for the model-based development of digital twins in smart manufacturing.

The paper is outlined as follows. Section 2 gives an overview of the related work, Section 3 introduces a running example of a smart factory, which is used to illustrate the approach and showcase the benefits of using a goal model as a digital twin. Section 4 introduces the approach under investigation to derive the goal models of the system and the digital twin. Section, 5 discusses findings from the applying goal modeling to specify a digital twin for our industry use case. Finally, Section 6 concludes the paper.

2. Related work

Research on goal modeling often focuses on the development of profiles to accustom the needs of specific application domains and systems. A comprehensive review of the goal modeling research field is given by Horkoff et al. in [11].

Recently, the systems and components under development or investigation are often modeled as actors rather than the stakeholders [12]. This, is particularly the case for describing modern system types. Therefore, various iStar profiles have been proposed for the development of cyber-physical systems (CPS, e.g., [13, 14]) or systems-of-systems (SoS, e.g., [15, 16]). The idea behind these approaches is viewing the CPS as interacting, collaborating, or competing actors. Thus, the focus of investigation moves from the original questions *'Can we fulfill all requirements of the involved stakeholders?'* and *'Which stakeholders are in conflict with one another?'* to *'Are different systems compatible?'* and *'Will they collaborate correctly?'* [17]. In this sense, correctness and compatibility is assumed when two systems can work together and the desired goals of both systems or of an overall system network can be fulfilled. The goal modeling approach in this paper, is oriented on this idea, as we also describe CPS that collaborate in a SoS.

For the use of goal models at runtime, various approaches exist. Most famously to mention is Tropos4AS [18] and extensions thereof, such as a recent approach by Morgan et al. [19]. These approaches extend the goal modeling language (most commonly iStar) with explicit context modeling [20]. This allows, among others, monitoring and proposing adaptations due to recognized context changes. Other approaches, e.g., the approach by Dalpiaz et al. [21], focus on the interactions between different actors, and define adaptation strategies for these. In contrast, our approach does not focus on the context to be monitored, but aims at providing support for monitoring the system (i.e. for developing a digital twin).

Monteiro et al. [22] proposed the use of goal models to develop a digital twin for vertical farming. They showed that the use of goal modeling has benefits for developing a digital twin. In our case, we want to systematically evolve the goal model of the original system, rather than create a digital twin goal model from scratch. In addition, contrasting the approach of Monteiro et al., we want to stick as close as possible to standard goal modeling languages (i.e. GRL and iStar) to reduce the number of modeling elements needed for describing the digital twin.

3. Case example: Smart factory

A smart factory (also referred to as U–Factory (ubiquitous factory), or factory of things) is a highly digitized and networked production facility [23, 24], whose concept is based on two major ideas:

- Smart manufacturing aims at completely monitoring the factory and its production processes for deriving ubiquitously valuable knowledge created/managed by the factory (or its digital twin). This allows, among others, for optimization of production processes[25], fast error response [3], and long term improvements of the smart factory.
- Flexible production aims at defining production processes based on the product. Thus, a smart factory is designed to develop a plethora of different products that are unknown at design time of the smart factory [26]. In traditional industry automation, the product is defined first (i.e. as CAD model), and then the production process (i.e. the bill of process) is defined. The production process specifies how this product shall be produced. Finally, a factory is built or re-organized in accordance with the production process. In contrast, in the smart factory, the factory is build first. The production process is defined based on the product specification and the factory's available capabilities [27].

In our research, we use an assembly line as a case example. The assembly line consists of a set of collaborative robots equipped for different welding purposes. Along this setup, there exist multiple monitoring systems needed for the digital twin, which are attached to every cobot station that analyze the execution of the respective process step. There are three important things to monitor: (1) the position of the cobot and the work piece, (2) safety aspects, (3) the outcome of the process.

Currently, research on digital twins mostly focuses on the later phases. Therefore, research questions are often data-centric in nature to derive precise predictions to trigger adaptations. As various reasoning approaches have been proposed for goal models, goal models might also be an interesting mean to support runtime analysis of the digital twin. However, in this paper, we want to focus on the preconditions, i.e. whether manufacturing systems as well as their digital twins can benefit from using goal models for their specification. We will investigate whether modeling specific objectives and requirements of the respective welding processes is possible and provides support for the development of digital twins. For the case example. we specified distinct goal models for the different participating cobots and their monitoring systems, and their interrelations.

4. Application to the case example

4.1. Overview over the goal modeling approach under investigation

In previous work, we have already shown that iStar [12] and the GRL [28] are good modeling languages to describe collaborative CPS in the industry automation domain [29] and proposed a GRL compliant iStar extension [14] to foster a systematic yet structured approach to specify collaborative CPS. In this paper, we use this approach to also specify the digital twin, based upon the specification of the system. Therefore, a two-step modeling approach is used. First, the smart factory and the individual cyber-physical production and transport systems of the smart factory are defined using a GRL goal model. Based on the goal model, the digital twin is defined. Therefore, the initial goal model shows the working steps of one of the cobots and the outputs it should achieve at the end of the process. Note that this simplified process illustrates how the digital twin can be developed using goal modeling. However, for a practical application - as we will discuss in our findings - a more nuanced process including iterations is needed, as the design of the digital twin influences the system design and vice versa.

4.2. Modeling the physical twin

We need to ensure that the goal model can be properly connected to the real world. Important for linking the goal model to the real world are tasks. According to the Z.151 standard [28], tasks are defined as "a set of instructions that are executed by a system in order to accomplish a specific goal or objective." They emphasize on the functional nature of tasks and highlights their purpose in achieving specific outcomes. Thus, tasks are an abstract description of the behavior of the system. This in turn can be monitored, and its fulfillment can be determined. Therefore, we restrict the leafs of the goal graph to be tasks, as this allows for proper monitoring.

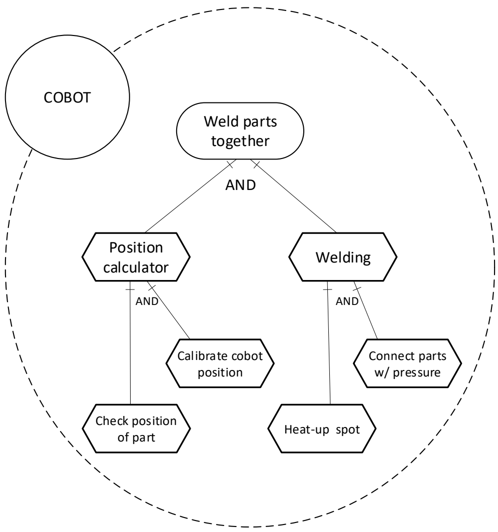

Figure 1: Goal model of the spot arc welding cobot

Figure 1 shows this restrictive modeling approach for the smart factory. Looking into how the assembly line is designed, it is visible that the whole process is divided into individual tasks and each end-effector completes a particular task. In Figure 1, we focus on just one of these cobots conducting spot welding tasks to assemble the car's doors to the chassis.

The goal model shows all tasks the cobot needs to execute in order to weld the door to the chassis. Therefore, the cobot needs to calculate the position, and then it needs to move the spot welder to that exact position and weld the door to the car. The sub-tasks "check position of part" and "calibrate cobot position" are essential, first the position of the part in relation to the position of the cobot arm is determined and then subsequently the cobot needs to be calibrated accordingly. The welding consists of two aspects, which are also specified as tasks. The cobot needs to pre-heat the welding spot and thereafter put pressure on the materials to actually weld the door into the chassis.

4.3. Modeling the digital twin

Next, we define the goal model for the digital twin. Therefore, we extend the goal model of the cobot (Figure 1) with aspects needed for properly executing the digital twin. The resulting goal model for the digital twin is shown in Figure 2. Most notably, we added monitoring tasks to monitor system execution. We, explicitly, distinguish these monitoring tasks belonging to the digital twin, from the execution tasks belonging to the system.

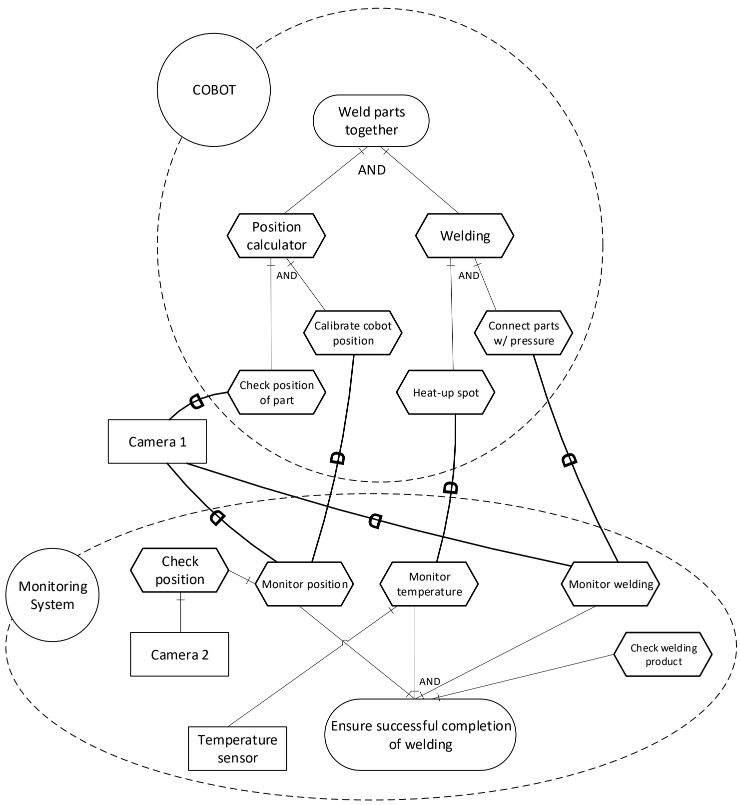

Figure 2: Goal model of the digital twin, including the monitoring system

There are also multiple sensors and cameras located to monitor the system during run-time. There are certain possibilities where system malfunctions can happen. These further defined monitoring tasks are dependent on the process tasks of the cobot. This allows us to express, which process task is monitored by which monitoring task. In addition, we can define further monitoring tasks that are not directly related to the process tasks. For instance, we can define a monitoring task to monitor the work product after all the process tasks have been successfully executed.

5. Findings from application

We evaluated the use of GRL goal models to model industrial production systems and to define the digital twin using goal models using the case example outlined in Section 3. As a first result, we can state that GRL is appropriate to specify not only the robotic systems in manufacturing use cases, but also the digital twin. Furthermore, we found that building the digital twin goal model upon the system's goal model helps in specifying the digital twin. Particularly, this offers support to identify tasks of the digital twin and to directly link them to the real world tasks and processes, aiding in the definition of appropriate monitoring and data gathering strategies.

For our second question, i.e. identifying specificities and requirements for a goal modeling approach to specify digital twin in industry automation, we recognized modeling patterns in the system model and the digital twin model that can aid in defining a structured approach.

For the modeling of cobots in the production process, we have – at least in our industrial case example – always two major branches:

- **The calibration** where the cobot identifies its position, the workpieces position, and checks for safety concerns (e.g., humans or other cobots are blocking the work space).
- **The execution** of the production step. Here, we typically see some pre-processing (e.g., heating up the mounted tool) and the actual processing (e.g., spot welding).

For the monitoring system, we also see patterns. First, we mirror the production tasks with monitoring tasks, second we need independent visual (e.g., a second camera as we cannot rely on just one camera) and other sensors as well as a final monitoring task that does not monitor the process execution but the result of the process. We checked this with other industry examples from automated production processes and discussed this with industry experts.

In addition, we found two specifics that should be addressed with a modeling approach. First, there is a need for specifying the production processes and linking these to the monitoring process of the digital twin. While the process steps can be modelled using tasks, the goal model does not specify any kind of execution order. However, for defining the tasks of the digital twin this is crucial as the identification of defects not only relies on the current step monitored but also on the outcome of previous production steps. Second, there is a need to specify different kinds of dependencies. It is important to differentiate between a dependency from the monitoring system needed by the digital twin to the system and between other dependencies i.e. between different cobots or even between monitoring system and cobot, which are not grounded in the digital twin, but stem, e.g., from usage of shared resources.

6. Conclusion and future work

In this paper, we investigated the use of GRL goal models to develop digital twins in the industry automation domain. GRL goal models allow for easy documentation of high-level requirements and their interrelations. We have shown that GRL goal models are applicable to model not only the cyber-physical production systems within a factory, but also the needed monitoring systems belonging to the digital twin. This way, the digital twin can be developed closely linked to the individual goals of the systems to be developed. In consequence, it can be ensured that every major production step – which is defined as task contributing to a major goal of a production system – is monitorable and will be monitored by the digital twin. In addition, we identified requirements to be considered when designing a goal modeling approach for digital twins in smart manufacturing, as well as some useful modeling patterns. Thus, for the future, involving fine-grained patterns in the goal-based definition of robotic production systems and their digital twin can help in easier definition and also support the analysis by pre-configured steps. Furthermore, for future work we plan to investigate the use of digital twin goal models as runtime as the existing reasoning approaches can provide support to runtime analysis and thereby the definition of monitoring and adaptation algorithms of the digital twin.

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