A configurable partial-order planning approach for field level operation strategies of PLC-based industry 4.0 automated manufacturing systems

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ABSTRACT

The machine and plant automation domain is faced with an ever increasing demand for ensuring the adaptability of manufacturing facilities in context of Industry 4.0. Field level automation software plays a dominant role in strengthening the overall flexibility of manufacturing resources. Classical programming approaches based typically on signal-oriented languages result in disproportionate effort for ensuring necessary flexibility. To address this challenge, a novel approach based on artificial intelligence planning techniques is presented which is able to handle domain specific requirements while facilitating efficient, scalable problem solving. Throughout this article, a discussion of specific requirements on automated planning techniques for field level automation software in the machine and plant automation domain with respect to Industry 4.0 is provided. An intensive study on existing works and their drawbacks towards addressing these requirements is presented. The proposed configurable partial-order planning approach is based upon a combination of an adapted goal-based planning formulation and its reformulation by means of linear programming techniques. It is shown that the proposed approach is able to efficiently solve large planning problems by exhibiting positive scalability characteristics which indicates its applicability for real-size plants.

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1. Introduction

The application of modern information technology in the domain of machine and plant automation can be seen as the major technological driver of the often proclaimed fourth industrial (r)evolution (Drath and Horch, 2014) — also referred to as Industry 4.0. Cyber–physical systems will serve as conceptual base of those Industry 4.0 automated production systems for realizing intelligent, technical systems (Monostori et al., 2016; Lee et al., 2015; Anderl, 2015) which comprise of networked embedded computing systems for monitoring and controlling physical processes while taking locally as well as globally (i.e. via internet) available information into account (Lee, 2008; Rajkumar et al., 2010). A variety of works characterizing Industry 4.0 by means of design principles exist as e.g. Kagermann et al. (2013), Hermann et al. (2016) and Hehenberger et al. (2016). These works have five major principles in common: (i) connectivity and integration are building the fundament of Industry 4.0 applications which provide improved opportunities for (ii) collecting and processing data in (iii) a service-oriented and decentralized manner. As a result, the cyber space will seamlessly be integrated with the physical world, and thereby, facilitate novel applications for work 4.0 environments by means of (iv) assistance systems as well as (v) self-organization and autonomy of machines and plants. Each of these topics has a long history in research and, accordingly, a huge set of promising results for each of them already exists. Nevertheless, the general concept of cyber–physical systems is not readily applicable in the machine and plant automation domain without additional research effort, which is mainly due to the specific combination of requirements like hard real-time, safety, dependability as well as established standards (Vogel-Heuser et al., 2013; Vogel-Heuser and Hess, 2016; Leitão et al., 2016). Furthermore, the objectives of Industry 4.0 comprise a synergetic combination of all (or at least some) of these topics which results in additional (not yet completely solved) challenges (Vogel-Heuser and Hess, 2016; Hehenberger et al., 2016; Leitão et al., 2016).

In order to strengthen and coordinate research and developments towards Industry 4.0, a set of industrial application scenarios and related research needs were defined by an industrial committee and scientific advisory board on demand of the German government (Plattform Industrie 4.0, 2016b). Thereby, the adaptability of future automated manufacturing systems plays an important role. In context of Industry
4.0, quick structural changes as well as changes of the technical process for manufacturing a specific good will be frequent and become daily routine. As a consequence, simple and fast changes of the plants’ layout and components as well as reconfiguring its behavior are important prerequisites for Industry 4.0 automated manufacturing systems. In addition, the assurance or even increase of the robustness by means of novel, sophisticated fault recovery mechanisms will characterize future Industry 4.0 plants (Vogel-Heuser et al., 2016). Towards realizing those application scenarios, and finally Industry 4.0 by design for future automated manufacturing systems, the aforementioned features like connectivity, service-orientation and autonomy play a crucial role. In particular, for achieving envisioned intelligent, self-aware and autonomous behavior, it is inevitable to implement automated problem solving techniques in order to facilitate autonomous decision making (Leitão et al., 2016; Anis et al., 2015; Lee et al., 2015).

Originated within field of artificial intelligence (AI) research, automated planning investigates the question how adequate strategies towards achieving a certain goal can be derived automatically (Russell and Norvig, 2009; Gallab et al., 2004). Applying automated planning techniques (also referred to as AI planning due to their origin) provide the opportunity to achieve higher levels of autonomy (Brachman, 2002; Russell and Norvig, 2009), and finally provide the fundament for intelligent, technical systems (Biundo et al., 2003; Beetz et al., 2007) as demanded in the context of Industry 4.0.

In a nutshell, for the addressing aforementioned application scenarios while considering design principles of Industry 4.0 for field level automation software, the application of an automated planning approach will shift the state of the art one step ahead. Thereby, especially the dominant importance of the field level in machine and plant automation and its specific characteristics has to be taken into account. Various researches on automated planning, both theoretical and practical, have been conducted yet, but due to underlying assumptions like connectivity, service-orientation and autonomy play a crucial role. In particular, for achieving envisioned intelligent, self-aware and autonomous behavior, it is inevitable to implement automated problem solving techniques in order to facilitate autonomous decision making (Leitão et al., 2016; Anis et al., 2015; Lee et al., 2015).

The remainder of this article is structured as follows: In Section 2, the requirements on an approach for automated planning of operation strategies in the machine and plant automation domain are described in detail. Subsequently in Section 3, techniques and approaches for automated planning in general as well as their application in the machine and plant automation domain in particular are discussed. An overview on the conceptual fundamentals of the proposed novel planning approach called HiTraP-AT is given in Section 4. HiTraP-AT relies on domain specific information for efficient operation strategy planning, and accordingly, a classical planning problem definition cannot provide sufficient information. Therefore, the HiTraP-AT planning problem is described as an extension of the classical problem definitions in Section 5. The novel planning approach presented here is based on two major contributions: a novel model reflecting domain-specific characteristics called hierarchical interconnected state space (presented in Section 6 and its formal definition given in the Appendix) and a Linear Program reformulation of this model for efficient planning (described in Section 7). The evaluation of the approach is given in Section 8 before finally summarizing this article in Section 9, respectively.

2. Requirements on AI planning for field level operation strategies

The machine and plant automation domain exhibit some specific characteristics which are reflected also within field level automation software. These characteristics are introduced in the remainder of this section and used to derive specific requirements to be fulfilled by a suitable approach on automated planning.

R1: Realization of the production process to manufacture a specific good

The overall objective when automating machines and plants is the (for sure automated) execution of operations for realizing a desired production process (Vogel-Heuser et al., 2014). Accordingly, an adequate planning approach needs to consider and plan an executable operation strategy which deals with realizing a production process for a desired good. We here assume a discrete production process as typically applied in manufacturing automation. To provide a maximum of freedom for the automated planning approach to be developed, the production process is solely specified by means of a definition of the raw material as a starting point for the production process and a suitable description of the final product. As a consequence, restrictions regarding potential valid production processes have to be given for the planner and must comprise aspects of the technical system as well as the material handling.

Example. A plant within the food and beverage industry for bottling liquids targets in producing capped bottles with desired filling. Starting point for each product is an empty, uncapped bottle which is typically delivered by suppliers as input material. An adequate production process contains operations to transform the input material into the desired product, i.e. filled, capped bottles.\footnote{A discrete process is characterized as a set of operations to be executed in a certain order. Each operation has a well-defined start and end. Discrete production processes comprise manufacturing but also batch processes.}

R2: Ramping up a manufacturing system

Manufacturing systems often do not startup directly in a state which enables starting production. Therefore, execution of functionality in order to transform a system into a state which enables starting production is required. In various cases, the initial state of a manufacturing system is not reached during productive operation. The reasons are manifold. In case of a failure, physical equipment and control software have to be synchronized (Andersson et al., 2010). Typically, such restart states are predefined and, in order to ease handling for human workers, physically reachable positions e.g. of robot arms, are preferred. In order to be energy efficient and protect from degradation of the facilities during unproductive phases, states of actuators are chosen which do not require much energy or force.

Example. Some positions of a crane module might not be part of the production process because it was chosen for easier access by human operation personnel.

R3: Mass production

The manufacturing of a good in high lot sizes (mass production) was introduced first by Henry Ford in context of the industrialization (Hounshell, 1985). In contrast, an upcoming trend to produce more and more customer-specific goods can be observed resulting in the trend to produce smaller lot sizes down to lot size one (Pine, 1999; Ramani et al., 2004). Methods and techniques to enable this so-called mass customization has recently been researched intensively. Nevertheless, in various domains like the manufacturing of convenience goods, mass production will remain the applied production paradigm. When manufacturing the same product in high lot sizes, efficient processes are inevitable in order to be profitable and competitive. Beyond such non-functional aspects, manufacturing the same product multiple times might require the execution of some of a machine’s functionalities which are not part of the main process to manufacture a specific
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