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A fault-tolerant approach to the control of a battery assembly system

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ABSTRACT

The paper concerns fault-tolerant control of a real battery assembly system which is under a pilot implementation at RAFI GmbH Company (one of the leading electronic manufacturing service providers in Germany). The proposed framework is based on an interval analysis approach, which along with max-plus algebra, allows describing uncertain discrete event system such as the production one being considered in this paper. Having a mathematical system description, a model predictive control-based fault tolerant strategy is developed which can cope with both processing, transportation and mobile robot faults. In particular, it enables tolerating (up to some degree) the influence of these faults on the overall system performance. As a result, a novel robust predictive fault-tolerant strategy is developed that is applied to the advanced battery assembly system. The final part of the paper shows the implementation and experimental validation of the proposed strategy. The proposed approach is tested against single as well as simultaneous faults concerning processing, transportation and mobile robots.

1. Introduction

Recent years have witnessed an increased interest in global competition on renewable energy market. One of the most rapidly developing segments of such a market is assembly of the energy storage systems which are applied e.g. in the electric vehicles, electronic devices, security systems, autonomous robots, mobile medical systems, etc. (Cao & Emadi, 2012; Dunn, Kamath, & Tarascon, 2011; Zhou, Zhao, & Tian, 2012). Currently, leading producers in this branch focus their efforts on developing more compact, cost effective, efficient and reliable battery storage systems for home use. Such battery systems allow house owners in combination with solar energy to become nearly independent from outside energy grid.

The RAFI Company has recently started to assemble such battery systems. Actually, the number of the assembled battery systems is relatively low because such a process is realized manually. However, intensified regulations and large predicted number of high performance batteries will not allow to apply this procedure in the future. Therefore, a flexible battery assembly system with autonomous robots will be introduced for high volume of serial production. This new production system is mainly based on transportation and manipulation robots. Thus, the main goal of the company is to set up the battery assembly system providing a maximal flexibility for upcoming variants of further battery system products simultaneously ensuring, a maximum quality and efficiency of manufacturing process and products reliability.

In order to fulfill such requirements it is necessary to combine agile manufacturing (Gunasekaran, 1999; Hasani, Zegordi, & Nikbakhsh, 2012) with appropriate process control strategies. The agile manufacturing by the appropriate organization of the manufacturing process and application of the suitable tools allows to respond quickly to changing customer needs controlling costs and quality. It can be applied at the assembly level of a manufacturing system. Such assembly system requires a definite level of flexibility (robustness, Kootbally, Schlenoff, Lawler, Kramer, & Gupta, 2015) due to the presence of disturbances of control factors and variance of process. The assumed system flexibility requires developing new control methods which can be correctly applied in the agile manufacturing system. Moreover, such method should tolerate some level of faults occurring in the manufacturing process ensuring its continuous work without lost of its efficiency.

To solve such a challenging problem the passive or active Fault Tolerant Control (FTC) (Blesa, Rotondo, Puig, & Nejjari, 2014;

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Farina, Guagardi, Mariani, Sandroni, & Scattolini, 2015; Fengming & Patton, 2015; Jiang & Yu, 2012; Zhang & Jiang, 2008) techniques can be applied. In the passive approaches earlier designed controllers are used to fulfill control specifications in nominal and faulty operation. They have to ensure that the controlled system or process is insensitive to certain faults. Unfortunately, the passive FTC techniques usually degrade the overall performance of the manufacturing process. In contrary, active FTC relies on reconfiguring control actions by adapting the control law to the faulty process behaviour (Paoli, Sartini, & Lafortune, 2011). In this case the acceptable performance of the manufacturing process is ensured. The reliability of the active FTC depends on the effectiveness of the Fault Detection and Isolation (FDI) systems (Chen & Patton, 1999; Isermann, 2011; Witczak, 2014) which are the integral part of the FTC scheme.

This paper is devoted to the developing and implementation of FTC approach for an agile battery assembly system which consists of transportation robots, assembly systems and input and output buffers. Such components are characteristic for manufacturing processes which are classified to Discrete-Event Systems (DES) (Paoli et al., 2011; Polak et al., 2004). DES are described as nonlinear dynamic systems with discrete inputs and outputs, and whose state can only change as the sequences of asynchronously occurring events over time. They can be modeled by finite state automaton, Petri nets, extended state machines, event-graphs, formal languages, generalized semi-Markov processes, nonlinear programming, (Abrams, Doraswamy, & Mathur, 1992; Hillion & Proth, 1989; Liu & Li, 2008; Sahner, Trivedi, & Puliafito, 2012; Yan, Dridi, & El Moudni, 2013). In order to restrict the behaviour of a DES to a desired scope, supervisory control theory is required (Ramadge & Wonham, 1987) which has been already investigated within several contexts (Balemi, 1994; Debouk, Lafortune, & Teneketzis, 2003; Park & Cho, 2006; Tripakis, 2004).

It should be underlined that the model of DES can only process classical state transitions so without uncertainty. However, in practice it is quite easy to find situations where the state transitions of systems are imprecise, uncertain and unclear. In order to solve such situations, for the example the extension of classical DES to fuzzy DES can be applied (Lamperti & Zanella, 2006; Liu & Li, 2008). It should be underlined that such systems have been successfully applied in communication systems, networked systems, manufacturing systems and automated traffic systems (Kumar & Garg, 1995; Seatzu, Silva, & van Schuppen, 2012; Takai & Kumar, 2012).

In this paper, a novel approach dealing with the problem of the uncertainty description of the DES model along with possible simultaneous production and mobile robot faults is proposed. In particular, the discrete event interval max-plus algebra (Baccelli, Cohen, Olsder, & Quadrat, 1992; Butkovic, 2010) to settle the robustness problem is applied. The initial idea concerning this line of development was to employ MPC (Model Predictive Control) to a simplified battery assembly system that pertains wiring and cell mounting (Majdzik, Seybold, & Witczak, 2014) only. This part of the entire battery assembly systems was described using a simplified model containing 5 states variables, only. The idea of MPC was further extended to cope with mobile robot faults (Seybold, Witczak, Majdzik, & Stetter, 2015a). The final stage of the development was devoted to the design of the simplified FTC algorithms that were able to cope with production faults (Seybold, Witczak, Majdzik, & Stetter, 2015b). As a result, a novel FTC approach, on the basis of MPC, was developed (Camacho & Alba, 2013; Witczak, 2014). The application of such a technique allows to optimize the efficiency of the assembly process satisfying all manufacturing process constraints in spite of the existing variations in parameters of the manufacturing process. The contribution of the current paper is to present new developments in this line of research, which are twofold. First of all, a new algorithm is proposed that is directly devoted to cope with possibly simultaneous production and mobile robot faults. The production fault test is described in an exact form, which was not the case in former papers (Majdzik et al., 2014; Seybold et al., 2015a, 2015b). Moreover, the robot performance constraint is described in a completely different and time-varying profile allowing to incorporate particular robot characteristics. Secondly, a simplified part of the battery assembly system is replaced by the full one, which contains 9 states variables resulting in a definitely more complex model, which reflects full spectrum of system behaviour and allows its implementation to the pilot plant.

The paper is organized as follows. Section 2 provides a comprehensive description of the battery assembly systems being at pilot implementation at the RAFI company. A robust modelling framework is provided in Section 3. It shows the symbolic model of the considered production systems and ends with its robust implementation which is based on interval analysis and max-plus algebra. Subsequently, based on the general model predictive control, Section 4 proposes a novel fault tolerant control scheme. The proposed strategy is validated in Section 5. Finally, the last section concludes the paper and indicates future research directions.

2. Overview of the battery assembly system

Currently, more compact, cost effective and efficient battery storage systems have been developed for home use. Such battery systems allow house owners in combination with solar energy to become nearly independent from outside electrical energy and greatly reduce the cost for electrical energy. The German company RAFI has recently started to assemble such battery systems. Right now, this company is assembling a low number of battery systems and the assembly is realized manually. Intensified regulations and large predicted numbers of high performance batteries will not allow this procedure in future. Therefore, a flexible battery assembly system with autonomous robots will be introduced for high volume serial production. This new production system is based on transportation and manipulation robots, additionally a few hand assembly system will be present. The main goals of the company are to set up a battery assembly system providing a

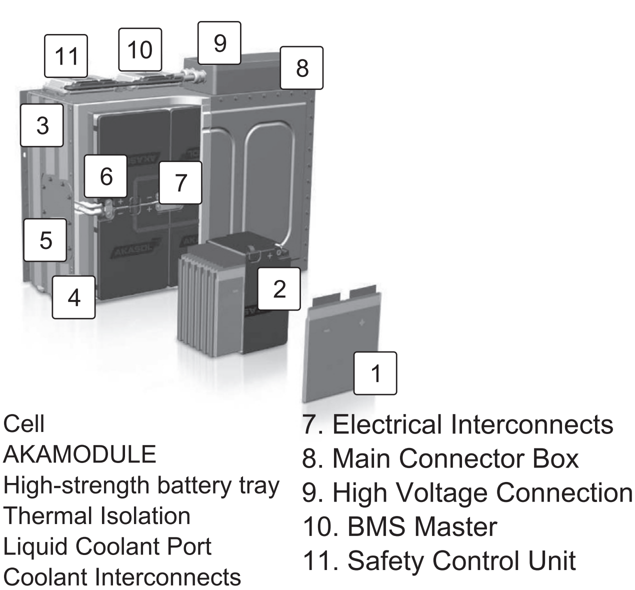

Fig. 1. Battery system.