CIRP Annals - Manufacturing Technology 64 (2015) 399–402

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Optimization of selective assembly and adaptive manufacturing by means of cyber-physical system based matching

Gisela Lanza (2)*, Benjamin Haefner, Alexandra Kraemer

wbk Institute of Production Science, Karlsruhe Institute of Technology (KIT), Kaiserstr. 12, 76131 Karlsruhe, Germany

ARTICLE INFO

Keywords:
Assembly
Quality assurance
Tolerancing

ABSTRACT

In high-tech production, companies often deal with the manufacturing of assemblies with quality requirements close to the technological limits. Selective and adaptive production systems are means to cope with this challenge. In this context new measurement technologies and IT-systems offer the opportunity to generate and use real-time quality data along the process chain and to control the production system adaptively. In this article, a holistic matching approach to optimize the performance of selective and adaptive assembly systems is presented and its industrial application within an automotive electric drive assembly is demonstrated.

1. Motivation

In today's high-tech industries such as micro [1] or automotive production (e.g. of crankshafts, pistons or electric drive rotors) [2–4], the requirements to the product quality in more and more cases approach the technological limits of the potential manufacturing processes. In particular, for assemblies with very small tolerances, the manufacturing processes of the components are either not capable of guaranteeing the required precision or only at very high cost.

Yet, the ongoing evolution of information and communication technologies (ICT), characterized by increasing computational capacity, functionalized sensor technology and ubiquitous network structures, is a means to cope with this challenge. By their integration into production facilities so called cyber-physical production systems can be created [5]. These enable intelligent interactions of the physical elements as well as adaptive and decentralized control of the system. This development commonly is referred to as "Industrie 4.0" associated with the understanding of a fourth industrial revolution.

As an enabler ICT provide great potential to be exploited for the aforementioned challenge of the production of high precision products at reasonable cost and to compensate limited manufacturing capabilities. By the conduction of inline measurements within the process chain, real-time information about quality characteristics at all critical production stages can be gathered. It is expected that cost-efficient inline sensors will be available as a commodity for many purposes in production in the future. Using the sensor data, real-time control in production can be facilitated.

The characteristics of the production system, in general, can be altered at three degrees of freedom:

- Selective assembly: matching of compatible low-precision components to achieve an assembly of high precision.
- Adaptive manufacturing: manipulation of manufacturing parameters to build suitable components for assembly.
- Product co-design: adjustment of the component design to conceptualize suitable components for assembly.

Within the scope of this article only selective assembly and adaptive manufacturing are considered. Both approaches have in common that the complexity of the limited manufacturing processes is mitigated to an increased structural complexity of the production system [4]. In this article, a new approach of selective assembly and adaptive manufacturing is presented in which the configuration of the production system is optimized in real-time by means of inline quality measurements.

2. State of the art

Selective assembly has been investigated by many researchers. Most approaches on selective assembly are based on the idea of partitioning components into classes of equal width. Regarding this issue, various statistical methods have been developed to find optimal binning strategies, e.g. by Mease et al. [2], Matsuura et al. [3] or Kannan et al. [6]. Fang et al. [7] propose methods based on classes with equal probabilities. Kannan et al. [8], Babu et al. [9], Asha et al. [10] and Kumar et al. [11] present different optimization algorithms for the matching of tolerance classes based on particle-swarm-optimization, artificial immune systems or genetic algorithms. Raj et al. [12] introduce a genetic algorithm to optimally mate the components within a batch. Some other

---

* Corresponding author. Tel.: +49 721 608 44017.
E-mail address: gisela.lanza@kit.edu (G. Lanza).

http://dx.doi.org/10.1016/j.cirp.2015.04.123

approaches also incorporate adaptive manufacturing in selective assembly. Akansel et al. [13] present an approach in which the manufacturing settings of one of the components can dynamically be adjusted. Iyama et al. [14] developed an optimal corrective assembly approach including reprocessing of components. Reprocessing and optimal fitting algorithms have been studied at wbk Institute of Production Science in the complex case of space frame structures [15]. Schmitt et al. [16] developed a self-optimization method for the adaption of manufacturing parameters in a process chain. Arai [17], Codellani et al. [3] and Kayasa et al. [18] developed process models to analyze various effects of production systems with selective assembly and adaptive manufacturing such as machine reliability or work in progress. While most of the approaches are restricted to the matching of only two components, some also deal with three ones, e.g. [8,9,12]. At wbk Institute of Production Science, currently, an approach for individual mating in the specific case of magnets in rotor assembly without partitioning into classes is studied [19]. Utilizing ICT, a concept for RFID-based, situational shop floor control was recently developed by Engelhardt et al. [20], yet, not dealing with the challenges of selective assembly.

In summary, it can be found that currently there is no research approach dealing with selective and adaptive production systems which considers the following aspects in detail:

- Methodology for the real-time optimization of a selective and adaptive production system with inline quality measurements.
- Optimization algorithm for individual matching of components based on their specific measurement values in real-time.
- Selective assembly and adaptive manufacturing for assemblies with more than three components.

3. Research approach

To overcome the aforementioned limitations, in this article a research approach is presented which enables an adaption of a production system based on inline quality measurements at relevant intermediate steps of the process chain in real time.

3.1. General model of the cyber-physical production system

The model of this research approach, illustrated in Fig. 1, focuses on a production system consisting of two process chains of manufacturing processes P_1 and P_2, whose final components are joined in an assembly station A. The model incorporates that an arbitrary number of the component types 1 and 2 has to be assembled for the final product. Without loss of generality the process chains of the two components can be considered as two single manufacturing processes. Cost-efficient inline metrology, e.g. using optical sensors, enables to measure the quality of each component and the final product at inline inspection stations Q_1, Q_2 and Q_{final}. Furthermore, the cyber-physical production system comprises an adaptive controller as well as a knowledge base. After the inline inspection stations Q_1 and Q_2 the inventory I_1 and I_2 are located, in which the two component types can be stored. It is assumed without loss of generality that the process capability of process P_2 is equal or higher than that of P_1. Thus an adaption of the manufacturing processes can be realized by a shift θ_2 of the nominal value of the resp. parameter p_2 of process P_2.

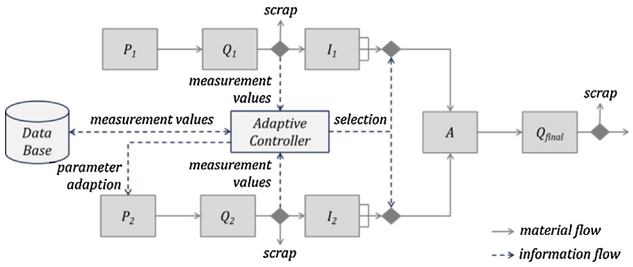

Fig. 1. Model of the considered cyber-physical production system.

3.2. Adaptive control of the cyber-physical production system

The adaptive control of the cyber-physical production system is realized by virtually mirroring the real production system in a discrete event simulation to represent its cause–effect relationships as realistically as possible. By means of a data interface the measurement values of the inspection stations can be imported to the control software. After the execution of optimization algorithms in the control software, the resulting control commands are forwarded to the real production system in real-time. The adaptive controller is capable of dynamically and autonomously optimizing the production system by means of simulating and evaluating potential control options simultaneously. The optimization is based on genetic algorithms. Thus, at each point in time the best configuration with regard to selective assembly and adaptive manufacturing can be selected. The optimization of the controller is divided into two time horizons with structural and real-time control cycles (Fig. 2).

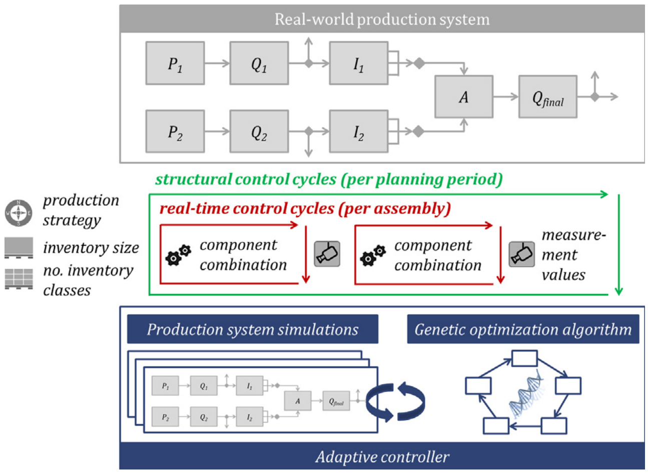

Fig. 2. Structure of the adaptive control.

3.3. Optimization algorithm of structural control cycles

In the structural control cycles of each planning period t the configurations of potential, predefined production strategies s are evaluated and the optimal one is selected. For this, the result of the real production system in period $t-1$ with its selected strategy s is compared to simulations according to the other strategies based on the quality measurements in period $t-1$. For each production strategy s the inventory sizes $n_{s,1}$ and $n_{s,2}$ and the numbers of classes $c_{s,1}$ and $c_{s,2}$ are optimized, being the relevant variables in selective assembly in addition to the production strategy. The overall objective in this optimization approach is the reduction of the total cost C of the production system, as in most cases this is the crucial evaluation criterion for its performance. Thus, for the optimization problems in the structural control cycles the objective function is defined as:

$$\min_{\Theta} C = \min_s \left\{ \sum_{i=1}^{N_{eff}(\Theta)} C_P(\Theta) + C_Q(\Theta) + C_I(\Theta) \right\} \qquad (1)$$

where C_P represents the production cost, C_Q the quality cost and C_I the inventory cost accumulating within the required period to produce a defined amount N_{eff} of good assemblies within the tolerance limits. C_P includes the cost for material, machines and personnel of all good assemblies. C_Q is defined as the scrap cost of the defective parts, which is given by their accumulated added values at the scrapping points within the process chain. C_I refers to the cost for storing the components of types 1 and 2 in the