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Approach for an event-driven production control for cyber-physical production systems

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Abstract

When the changing market environment in terms of logistical requirements is considered, production planning and control (PPS) has recently contributed significantly to fulfilling these demands. Cyber-physical production systems (CPPS) with their characteristics of decentralised organisation, real-time capability and smart data processing offer new possibilities for PPS.
Consequently, this paper proposes a new event-based approach. Control loops close to the production shop floor enable a rapid identification of events. Based on an activity list, production control is able to react adequately to different events, such as machine disturbances. Finally, the developed approach for event-driven production control is implemented in a simulation.

Keywords: Production planning; Control; Digital manufacturing system; Modelling; Cyber-physical systems

1. Introduction

Costumer and customer-orientated services are becoming increasingly significant in a globalised world. This causes manufacturing companies to adapt to changes in economic demands and to react to in-house events [1, 2].

1.1 External Changes

This development is marked by a growing demand for individual product variation, shorter product cycles and increasing production complexity, as well as fluctuating order intakes [3]. At the same time, there are also demands for shorter delivery times and the more precise observation of delivery schedules [4].

As a result, an increasing complexity in organisation and controls as well as the implementation and surveillance of production cycles can be observed [5]. These challenges cannot be satisfactorily solved by standard approaches in production organisation and controls [6].

A paradigm change is needed in order to cope with complexity and increasing dynamics. The reduction of the capability to implement minor changes in production planning is routed in a relocation of decision-making from a centralised hierarchy to decentralised units [7, 8]. The resulting responsibility of the decentralised decision-making units lead to the separation of complex tasks and to shorter reaction times in the event of unpredictable situations or disruptions [8]. Reducing current stocks in favor of shorter throughput times the whole production process results in a much narrower linkage of product recourses to each other. The variability of a product resource influences the production steps and therefore the whole production system much more strongly. Planning and controlling concepts, which are not in line with these dynamics, will eventually increase instability within the process development [9].

1.2 Internal Changes

Besides the above-mentioned external changes, there are also internal changes that trigger events within the production environment [10]. Unforeseen events during the order processing, such as rush orders, machine failure or missing components disrupt and delay production cycles. These

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unexpected events are commonly described as disturbances in the literature [11, 12]. In publications, diverse identification and categorisation models exist for disturbances. The REFA has introduced a disturbance categorisation. Disturbances are regarded as events which have an influence on the set / actual state of a production. External errors have natural, governmental or economic reasons [13]. The causes of internal disturbances include supplier, production or sales factors. In their categorisation, Warnecke and Jacobi focus on disturbances in production and add workers, department, material and information to internal disturbances. These causes can further be separated into technical and organisational disturbances [14]. Overall, the individual categories of unforeseeable events and/or disturbances are genetically built and constructed. In addition, they are on a high to abstract aggregation level [15]. This leads to greater numbers of different disturbances within the production environment.

1.3 Future Requirements

Internal and external challenges in production requires on modern production planning and control procedures. In the future, production structures will have to be rapidly adapted to changing goals. Requirements are:

- The implementation of a control circuit to increase the ability to react faster
- Dynamic prioritization of logistical goals within production sectors
- Transfer of most statistic production controls to a dynamic production control

In order to meet the tasks and requirements in the wake of the upcoming Industry 4.0, closed loop control methods are used in production.

2. Entities and influences of CPS-based production

Cyber-physical systems (CPS) represent promising approaches to these challenges, due to such capabilities as *ad hoc* connectivity, self-configuration and decentralised, intelligent data processing [16]. These products and product components are deemed intelligent and contribute to cyber-physical production systems (CPPSs) [17].

2.1 Cyber-physical production systems

Cyber-physical production systems are marked by the connection of real (physical) objects and processes with information distribution (virtual) objects and processes on open, partly global and constantly connected IT networks [16].

The classical automation pyramid shows (next to the functional structure of an automation system) the intensification of data and information in the nodes. The automation pyramid is gradually being extended to its functional structure through the possibility of the usage and provision of central services and CPPS [18]. Real-time critical controls will mainly remain close to the shop floor processes.

It is possible that in the future, real-time demanding applications can be handled by distributed CPPS architectures [19].

2.2 Cyber-physical systems

The structure of cyber-physical systems is best explained by the "onion principle". These systems portray the system of systems principle, meaning that systems can be repeatedly combined with others to create systems of a greater hierarchy [20]. This enables CPS to implement a few new functions, services and characteristics that surpass the capabilities of today's embedded systems. CPSs can grasp their diverse application and environmental situations instantly, change together interactively with the user and control their behavior in anticipation of the individual situation.

These systems perform their tasks as follows [18, 21]:

- Mostly independent of the location
- Context-aware
- Adapted to the requirements of the current situation
- Partially autonomous
- Multipurpose and
- Connected and distributed for the individual user and stakeholder

2.3 Specification of production control

The VDI (1992), the classification scheme by Hackstein (1998) and the production model by Lödding (2016) define production control. These definitions are incongruous in the classical sense of closed-loop control theory [22, 23].

The German Institute for Standardisation (Deutsches Institut für Normung (DIN) defines control as a process within a system, whereby one or more input variables influence output variables through the systems internal regularities [24]. Systems such as those just described are referred to as "open loops". Open loop controls do not directly monitor the triggered actions and consider them in the upcoming control action.

In comparison, the so-called "closed loop control" is a process in which the control variable is continuously compared with the command variable and is influenced in the sense of an adjustment to the command variable.

Characteristic for the closed loop control is the closed action sequence, in which the control variable in the path of the control circuit continuously influences itself [24].

Because the process controls are based on the outcomes of former measures and reacts to unforeseen events, the word "control" is preferred to the word "regulation", which is more commonly used in the literature [25]. Concerning the goal of this paper, the term "production control" will be used.

2.4 Event-driven production control

Within production planning and control, technical incidents with a variety of different causes trigger events. These might be unforeseen or unexpected incidences [12, 13]. The expected events from production are, for example, logistical operations, feedback from the beginning or end of working operations and the operating equipment used.

These incidents are pre-determined time wise by planning and trigger further internal events. Unexpected events during order processing such as rush assignments, machine failure or missing operating equipment have a disruptive effect in the form of interruptions and delays during production. These incidents need to be detected early and counteracted. Because the constant gathering of values and status conditions leads to an unnecessary amount of data, event-triggered systems are more efficient in this situation [26, 27]. Hence, the terms "sampling frequency" and "real time" have to be defined.

2.5 Real time and sampling frequency

A real-time system is one that responds to a signal, event or request quickly enough to satisfy a specific requirement [28]. The Nyquist-Shannon sampling theorem constitutes a master guideline. It states that the exact reconstruction of a continuous-time baseband signal from its samples is possible if the sampling frequency is greater than twice the bandwidth [28, 29]. According to the Nyquist-Shannon sampling theorem, a maximisation of the level of resolution, both in terms of detail as well as in promptness of information, is not the objective. In contrast, the appropriate level of resolution needs to be adjusted depending on the specific use case [30].

For achieving the goal of event-driven production control, a method for determining the sampling frequency is necessary.

3. Adaptation of Models

3.1 Modelling a CPS

In the literature, CPSs are often described as generic units that communicate with other systems and act autonomously. From the perspective of manufacturing controls, CPSs are the smallest entities controlling the production, such as drilling and milling machinery or assembly stations [31]. To integrate this resource into controlling, the corresponding theoretical controlling technique has to be modelled (please refer to Figure 1). The command variable w(t) of a product resource symbolizes the planned working process. The control deviation e(t) can be calculated by comparing with the current progress. If this leads to a significant deviation within manufacturing controls, a manipulated variable u(t) needs to be determined.

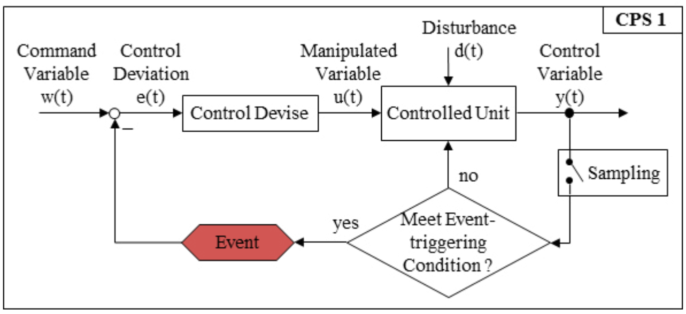

Fig. 1. Modelling a CPS based on regulations theory.

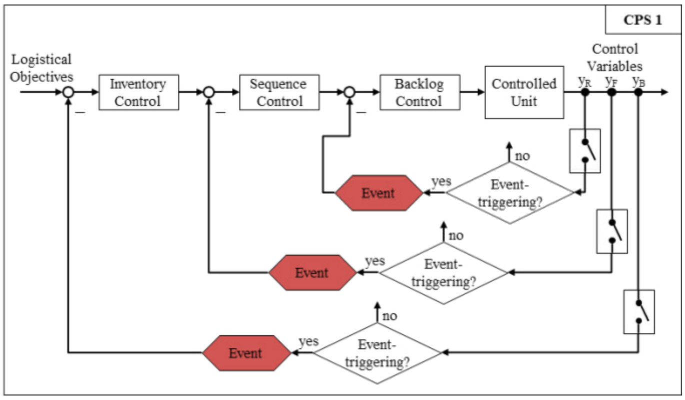

Fig. 2. Cascaded measures for production resources.

Value-creation processes such as drilling and deburring take place within the controlled unit. These processes are influenced by incidents such as defective tools and missing material, which slow down working processes. The time needed to discover these incidents depends on the sampling frequency. If delays are detected during sampling, the corresponding events are triggered and, if necessary, the measures required are initiated.

3.2 Cascaded measures

If significant control deviations occur within the manufacturing progress, they have to be counteracted. In Figure 2, a cascading structure of possible counter measures is described [19].

Progress delays are first countered with a short-term capacity rising by the residue regulator, for example by raising the clock rate or feed rate of a drilling machine. If the product resource cannot supply the capacity increase demanded (backlog control), sequence and inventory control are executed. During sequence control, it is possible to alter the order release and lot size. During production, orders are released with respect to existing limits.

3.3 Extension of conformed production planning and control model

To find the optimum for the whole production system, the production plan is centrally created in the CPPS, not on a "local" CPS-based level. Hereby, every CPS contains an inventory, backlog and sequence control to ensure decentralization and transformability, see Chapter 3.1.

The CPSs communicate with other CPSs, as well as with the higher ranked CPPS. To demonstrate how the event sources can be lowered and planned inventory expanded, a model was created based on Lödding's production planning and control model. The extended control circuit also shows the information flow within a production resource.

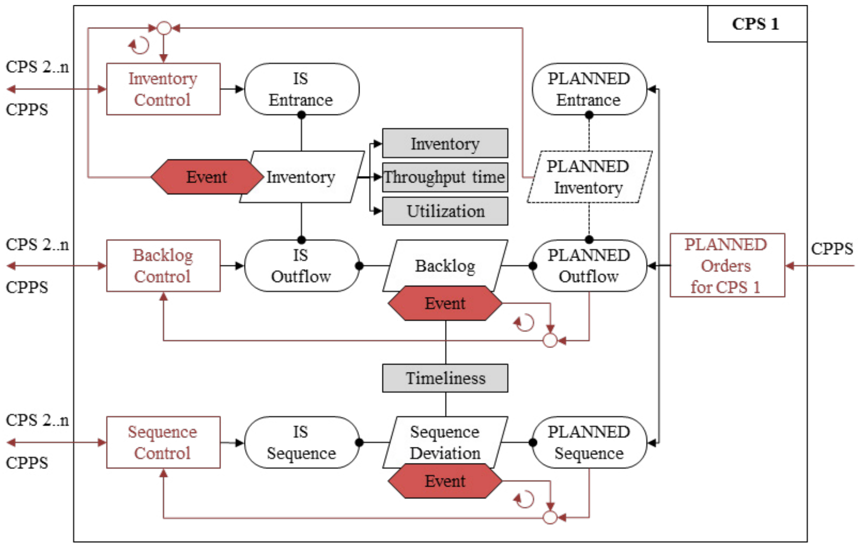

Fig. 3. Advanced manufacturing model for a CPPS.

3.4 *Method to determine the sampling frequency for CPPSs*

For calculating the sampling frequency for each production resource within the CPPS, many influencing factors must be taken into account . It ensures the necessary transparency over all processes. During the first step, all the vital resources for the production have to be identified. This results in a specific set of machinery for every assignment. The second step contains the specification of the control mechanisms. Possible procedures are, for example, a load-dependent order release or a constant work in process (ConWIP).

In a further step, the possibility of an increase in capacity for a production system is sought. This includes additional layers, minimisation of the set-up time, and an increase in clock rate or assembly speed. Furthermore, a cascading control circuit is implemented and relevant events are determined, see Chapter 3.2.

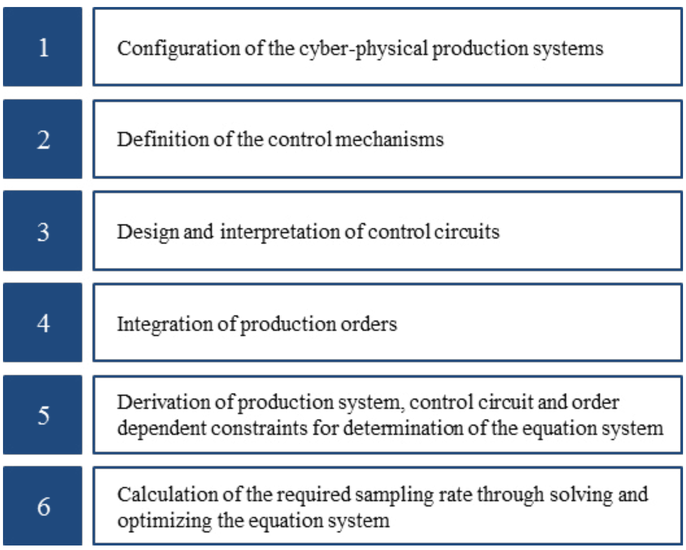

Fig. 4. Method for determining the sampling rate.

During the fourth step, production orders are integrated and the duration of the individual working steps and processing tasks are determined.Because working operations have inconsistent durations, this step has a great impact on the overall result. Having taken all necessary dimensions into account the fifth step is characterized by the derivation of production system, control circuit and order dependent constraints. Finally, the equation system needs to be solved and the frequency for sampling the control variable can be determined.

4. Application

As an example, typical disturbances and deregulating control schemes, which have been developed during the event-based concepts of a production control, are implemented. By analysing the results of the simulation, which were acquired with or without the use of individual measures from the production control concept, optimisation potentials are being emphasised by corresponding measures.

To save time and money during optimisation, the approach presented was pre-tested in a simulation. In this particular case, the production system is modelled in Tecnomatrix Plant Simulation. The production of the focused gearing system consists of four working steps: Camera-based-quality-check, pick-2-light-station, drilling machine and assembly station. A working day with 8 working hours, a 15-minute break and a 30-minute lunch break was simulated. The production plan has been adjusted and allows the opening of two new assignments every 270 seconds. No new assignments are opened during breaks.

4.1 *Scenario*

The scenario shows the effect of different tools. During simulation, the case occurs that the rotary chisel of a drilling machine is worn-out so that the number of rotations has to be reduced in order to ensure an adequate surface quality. As a result, production takes longer than with a sharp chisel. A worker can change the worn-out part if it is discovered immediately. If it is not changed after a certain period of time, equipment breakdown or machine failure will result. The machines gather data and provide feedback if unscheduled events occur. This includes notifications at the end of a working process or if any interruption occurs.

4.2 Method

Table 1 shows the results of methods for the production of a gear system. During the first step, the production resources are being selected. Then, the BOA control mechanism is selected and it is determined whether the capacity of individual recourses can be increased. In this scenario, only the drilling machine may increase capacity, by increasing the number of personnel involved. Afterwards the lead time of one working step is determined and entered into the goal function. The calculated sampling rate can be seen in column 6.

Table 1. Determine the sampling rate.

Step					
1	2	3	4	5	6
Quality-Check	BOA	Not possible	132 s	Target function	7 s
Pick-2-Light	BOA	Not possible	86 s	Target function	4 s
Drilling Machine	BOA	Possible	701 s	Target function	35 s
Assembly Station	BOA	Not possible	185 s	Target function	9 s

A sampling rate of 35s has been calculated for the drilling machine. With this sampling rate, the following scenario for the drilling machine will be examined.

4.3 Recognising missing events

One aspect of the developed concept is the sampling of feedback data from the machine at the time when an event is expected. Depending on the sampling frequency, the local control unit detects either in defined intermediate steps (i.e. when changing a tool) or during the planned ending of a process. In the current scenario, tool exchange is triggered automatically because the process parameters indicate that the rotation speed has been reduced due to worn-out tools, which meant that the processing time had to be increased.

4.4 Analysing the situation

Figure 5 shows the graphs of the throughput times. Three cases have been simulated.

In the first case (blue, dotted line), the damage to the rotary chisel has not been discovered, while in the other two it has been discovered through sampling during the planned end time.

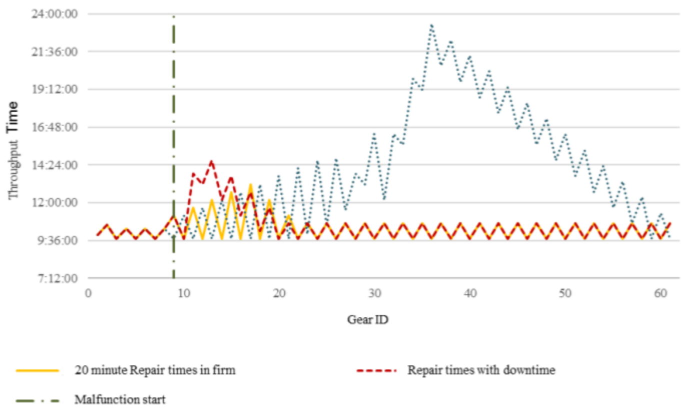

Fig. 5. Development of throughput times during tool wear.

During the second case (red, dashed line) the incidents cause a 10-minute machine stoppage and during the third case (yellow, through line) the maintenance took 20minutes of repair time during continuous operation. It is clear that the throughput time increases slightly during the first case once the incident has occurred. If the incident is not remedied in time, it will lead to a tool malfunction. The throughput time increases rapidly to a maximal value of 23 minutes and 20 seconds and only recovers slowly. In the two other cases, the longer processing time is discovered instantly and a technician can fix the problem before it leads to irreversible damage. Even after the production of nine gear systems (about 50 minutes), production can resume according to schedule.

This scenario shows clearly how important it is to discover incidents as early as possible. With closed loop control on the shop floor, deviations from production planning can be easily discovered and narrowed down to possible causes. Through constant comparison of control and command variables, occurred incidents could be signaled in the drilling machine process, even if the machine-data-detection unit has not set off an alarm. The cause of the incident could be eliminated before it could cause any significant long-term damage. Sampling, at the time an event was about to occur according to production planning, has proven itself to be very successful in revealing the absence of any confirmatory events.

5. Conclusion and Outlook

External and internal events are continuously changing the future of production. This shows that the possibility of disruptive events will increase in the future due to more complex processes and the stronger networking of production resources. No detailed classification of the total order processing is possible. This increases the importance of fast reactions to unplanned events. The recent research on CPS in the digitalisation of production and closed loop control in order to increase counter-measurements remain of high potential. The possible solutions are being expanded by using an event-triggered approach. With an event-controlled system, the required data needed for transfer can be reduced and waste of calculation capacity avoided. A fitting sampling frequency is needed to increase transparency. Since current systems are not designed for continuous data flow, the models have to be adapted to requirements during production. One element represents the transformation of a CPS and a control unit.

Thus, the procedures described within a production resource can be built into a model. The measurements within production control can be transferred into a cascaded control system. By adapting the production model, CPS and CPPS can be represented. Based on these models, the developed methods allows the calculation ot the required sampling rate.

The model depicted is still in its prototype phase, a real production environment is being sought to evaluate the methods and models.

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For more information about the ongoing research project, refer to the following website: www.openserv4p.de.

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