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Reactive control of overall power consumption in flexible manufacturing systems scheduling: A Potential Fields model

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ABSTRACT

In recent years, designing "energy-aware manufacturing scheduling and control systems" has become more and more complex due to the increasing volatility and unpredictability of energy availability, supply and cost, and thus requires the integration of highly reactive behavior in control laws. The aim of this paper is to propose a Potential Fields-based flexible manufacturing control system that can dynamically allocate and route products to production resources to minimize the total production time. This control system simultaneously optimizes resource energy consumption by limiting energy wastage through the real-time control of resource states, and by dynamically controlling the overall power consumption taking the limited availability of energy into consideration. The Potential Fields-based control model was proposed in two stages. First, a mechanism was proposed to switch resources on/off reactively depending on the situation of the flexible manufacturing system (FMS) to reduce energy wastage. Second, while minimizing wastage, overall power consumption control was introduced in order to remain under a dynamically determined energy threshold. The effectiveness of the control model was studied in simulation with several scenarios for reducing energy wastage and controlling overall consumption. Experiments were then performed in a real FMS to prove the feasibility of the model. The superiority of the proposition is its high reactivity to manage production in real-time despite unexpected restrictions in the amount of energy available. After providing the limitations of the work, the conclusions and prospects are presented.

1. Introduction

It is estimated that industrial power consumption worldwide will increase by 40 percent between 2006 and 2030 (Energy Information Administration, 2009), while power supplies will decrease due to the decline in fossil fuel-based energy sources (Chefurka, 2008). The manufacturing sector, which accounts for the biggest share of power consumption (33%) and greenhouse gases (38%), will have to cope with growing energy costs, the uncertainty related to renewable energy, new legislation regarding energy efficiency, and customers looking for sustainable production (Jänicke, 2008; Taylor, d'Ortigue, Francoeur, & Trudeau, 2010). That is why one of the IMS2020 project roadmaps (IMS2020, 2013) focuses on energy as one of the main concerns in manufacturing, the key area of Energy Efficient Manufacturing being to reduce the carbon footprint of manufacturing in the future.

There are many ways to design Energy Efficient Manufacturing systems since energy, typically electrical energy, can be considered in different stages of a product's life cycle, namely procurement, production, distribution and afterlife (Sarkis & Rasheed, 1995). This paper focuses on the production stage in manufacturing systems that play a vital role in the global economy, but have a significant environmental burden (Duflou et al., 2012). As outlined in (Pach, Berger, Sallez, Adam & Trentesaux, 2013a), during the production stage, different solutions can be studied to reach the desired sustainability: resources or processes can be substituted with less consuming ones; resource optimization can be enhanced; processes can be fine-tuned and external energy-saving devices can be added to the system.

The first possibility is to substitute processes or resources with less consuming ones. Regarding processes, (He, Liu, Zhang, Gao & Liu, 2012) show that using alternative process schemes for two jobs can greatly affect energy-optimizing scheduling. (Zein, 2013) presents current work on machine tools to make them more efficient. The problem with changing a process or resource is that first, it can imply other modifications in the manufacturing system and second, it requires heavy initial investment for the manufacturer (Bi & Wang, 2012). The second way to increase the sustainability of a manufacturing system is to adjust processes with regard to power consumption. Optimizing a process can greatly improve power consumption (Dietmair & Verl, 2009; Ochoa George, Gutiérrez, Cogollos

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Nomenclature

FMS notations

R	is the set of resources r.
Q_r	is the queue size of resource r.
SR_r	is the set of services provided by resource r.
$SR_{r,s}$	is the service s provided by resource r.
P	is the set of products p to be manufactured.
SP_p	is the set of services required by a product p.
$SP_{p,s}$	is the service s required by a product p.
$Co(t)$	is the consumption of all the resources at time t.
$Co_{i,r}$	is the consumption in state i of resource r, $i \in [1, 4]$.
$Co_r(t)$	is the consumption of resource r at time t.
$Th(t)$	is the energy threshold not to be exceeded at time t.
$Cmax$	is the total production time for a set of products P to be manufactured.

PF notations

$\alpha_{r,s}(t)$	attractiveness of resource r for a service s.
$S_{r,s}(t)$	is a binary value set to 1 if resource r is available for service s at time t and set to 0 if the resource is unavailable.
$w_{i,j,r}(t)$	is a binary value set to 1 if product j is waiting for its service number i in the input queue of resource r at time t, 0 otherwise.
$z_{i,j,r}(t)$	is a binary value set to 1 if service number i of product j is currently in progress on resource r at time t, 0 otherwise.
$\Phi_{r,d,s}(t)$	PF propagated from resource r, for a service s, sensed by any product at a decisional node d.
μ_r	denotes the magnitude that determines the range of the PFs emitted by the resource r.
$M_{r,d}(t)$	denotes the mitigation of the PFs by the environment (between resource r and node d).
r^*	the resource with the highest PF.
$\beta_{p,r,s}(t)$	intention from product p for resource r and service s.
$Z_{i,p}(t)$	is a coefficient that depends on the current state of the product.

Martínez & Vandecasteele, 2010). However, tuning the process implies good knowledge of the resource and the possibility of changing its parameters (e.g., speed, temperature). This can also lead to new problems, such as lower product quality or shorter resource lifespan. A third way to improve the energy efficiency of a machine is to add external devices to monitor or control power consumption (DMG, 2010). However, with these three technical solutions, the full potential to increase energy efficiency is not exploited (Pechmann & Schöler, 2011). Significant energy savings are attainable, but these three methods imply heavy investments for the necessary upgrades, refits and overhauls (Newman, Nassehi, Imani-Asrai & Dhokia 2012). Therefore, before investing in new machines or processes, or fine-tuning processes and power consumption, manufacturers have to consider: “Is my current manufacturing system used in the best possible way with regard to energy savings and restrictions?” This leads to the last way of improving the energy efficiency of the system: optimizing the scheduling and the control of existing resources by taking power consumption into consideration with regard to a level of available energy. In this way, resources and processes stay the same, and changes are made to the manufacturing scheduling and control system. The gain in energy can be significant (Devoldere, Dewulf, Deprez, Willems & Duflou, 2007). This paper deals with designing such energy-aware manufacturing scheduling and control systems.

In recent years, designing such “energy-aware manufacturing scheduling and control systems” has become more and more complex due to the increasing volatility and unpredictability of energy availability, supply and cost, and thus requires the integration of highly reactive behavior in control laws (Ghadimi, Kara & Kornfeld, 2015). For example, the carbon footprint is bigger during periods of peak load (e.g. electricity peak load) due to the use of more expensive and less clean sources (Prabhu, 2012). This can result in dynamic (i.e., real-time) electricity pricing. It is also important to note that, with provider–user energy supply agreements, exceeding the consumption defined will result in significant penalties. Another factor that will result in more unpredictable costs and availability, as well as volatile energy supplies, is the increasing use of solar panels or wind turbines in the energy grid. The evolution in the energy available has to be predicted, but the price, the load and the consumption behavior implied may be difficult to predict (Fan & Borlase, 2009; Ipakchi & Albuyeh, 2009).

In this context, the paper considers a specific but widespread kind of manufacturing system: flexible manufacturing system (FMS), and proposes a FMS control system that can reactively optimize and control the overall power consumption of the Flexible Manufacturing System, with a variable and limited energy supply that is hard to predict.

Section 2 thus presents some studies dealing with power consumption control in manufacturing systems and positions our contribution. Section 3 formalizes the problem and Section 4 presents a reactive Potential Fields model to control the FMS taking energy into consideration. The FMS case study is presented in Section 5. Section 6 reports the simulations performed for this case study. Section 7 provides clues for the implementation of concepts in this case and an experiment in real conditions. Section 8 presents the limitations of the approach proposed. Our conclusions and prospects are presented in Section 9.

2. State of the art in energy-aware manufacturing scheduling and control

Contributions found in the literature focusing on optimizing the use of existing manufacturing resources by taking power consumption into consideration with regard to a level of available energy are two-fold. The first and most common are mathematical programming oriented approaches. There are numerous studies using Integer Linear Programming (Zhang, Li, Gao, Zhang & Wen, 2012), Mixed Integer Linear Programming (Bruzzone, Anghinolfi, Paolucci & Tonelli, 2012; Fang, Uhan, Zhao & Sutherland, 2011a), Fractional Mixed Integer Programming (Wang, Ding, Qiu, & Dong, 2011) or Mixed Integer Non-Linear Programming (Vergnano et al., 2010). The first problem tackled in the literature is peak power consumption. Peak power consumption can cause huge peaks in the energy grid and generate additional costs (Pechmann & Schöler, 2011). (Babu & Ashok, 2008) tackled the problem using mixed integer non-linear programming that reschedules the load and minimizes the energy peak. The problem is also tackled in (Bruzzone et al., 2012) with a two-step approach where a schedule is created by an advanced planning and scheduling system without considering energy savings, and then refined using mixed integer linear programming to control peak power consumption. The second problem tackled is the reduction of the overall power consumption of the manufacturing system. In (Zhang et al., 2012), this is controlled with a linear programming-based scheduling function. In (Vergnano et al., 2010), the problem is solved using non-linear programming. (Fang, Uhan, Zhao & Suthedrland, 2011b)