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An energy consumption evaluation methodology for a manufacturing plant

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ABSTRACT

The energy efficiency of manufacturing systems is a topic of paramount interest, and reliable methods for modeling the energy consumption of machine tools are of fundamental importance for the design and management of production plants. For these reasons, this paper proposes a approach, named aCtuatorS Methodology (CSM), for modeling and predicting the energy behavior of discrete systems, i.e. systems where the energy consumption is mainly due to the on/off switching of the actuators governed by the control logic. CSM is then used to compute the energy consumption of the pallet transport line of a de-manufacturing pilot plant. A dynamic Discrete Event Simulator (DES) is first used to estimate the instantaneous overall energy consumption based on the absorbed power of each actuator and to complete a preliminary simulation study. The value of the energy consumption estimated with CSM is then compared to the real value measured on the transport line. The results achieved confirm the very good agreement between the behavior of the system predicted with CSM and the measured data.

Introduction

Improving the energy efficiency of manufacturing production systems is nowadays a topic of paramount interest. In fact, the need to limit the CO_2 emissions [1,2] resize the factory energy supply infrastructure, and minimize the energy consumption, represent factors that lead to equalize global living standards at the level of the industrialized regions [3] and to create new perspectives on energy efficiency in business decisions [4,5], besides saving plant installation and production costs.

In order to design and manage energy efficient factories [6,7], manufacturing companies require tools [8–11] for the prediction and computation of the energy consumption of process equipments (PE). Interesting reviews of the main approaches proposed so far can be found in [12,13]. Many of these methods are based on Discrete Event Simulation (DES), see e.g. [14,15]. In particular, the widely popular approach proposed in [14] introduces the concept of "Energy Block", i.e. the specific energy consumption behavior that a machine can assume in its operating states, like "turned-off", "start-up", "warm-up", "stand-by", "processing" or "stopping". By associating to each operating state an energy consumption pattern, identified by a power profile, it is possible to compute the overall energy consumption of the machines in different operating conditions. Further extensions of this approach have been reported in [15,16], where the plant auxiliary systems have also been considered. In [17–19] the operating states of the process equipments and the associated energy consumption have been modeled in terms of Finite State Machines (FSM), see [20–22], a formalism suitable for dynamic simulation. A refined approach has been implemented in [23], where three different aspects of PE are taken into account, namely the mechanical, the logic control algorithms and the energy characteristics. While the mechanical behavior is modeled by means of DES, the logic control and energy aspects are described as FSM. In any case, it must be recalled that the accurate knowledge of many plant parameters, which can be directly measured, computed, or derived from technical nominal data, is fundamental for the proper computation of the energy consumption of the machines, see [24–26].

A drawback of the approaches based on the use of Energy Blocks can be due to their limited flexibility and scalability properties. In fact, the number of operating states, and the associated required power profiles, are in general variable and depend on the specific product to be processed in terms of the machining operations and production process technology, the material to be machined, the topology of the system, the adopted control logic. Therefore, when

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these conditions change, it can be difficult to compute, or reliably estimate, the energy consumption and the power peak loads. Notably, this information would be very useful both to the plant designers and to the management engineers: for the first ones to optimize the factory layout still during the plant design workflow phase, while for the second ones to optimize the on-line control of the production system according to specific performance indexes.

Motivated by the above reasons, this paper proposes a DES-based approach for the computation of the energy consumption of discrete systems, i.e. systems where the energy consumption is mainly due to the on/off switching of the actuators governed by the control logic. In the proposed method, named aCtuatorS Methodology (CSM), the modeling phase includes both the mechanical behavior of the system and the analysis of the actuators' characteristics, typically electric motors or pneumatic actuators, in terms of their absorbed power. In this way the resulting DES model is suitable to dynamically describe the energy consumption due to the logic state (on/off) of each actuator managed by the emulated plant control system. Then, based on the actuators' absorbed power parameters, specified in terms of either field measurements or nominal data, the instantaneous power required by each machine [27,28], and by the whole production plant is computed. It follows that the evaluation of the energy behavior is largely independent of the factors defining the operating states of the machines and of the adopted control strategy, since it is based on the effective power instantaneously absorbed by the active actuators [29]. On the other hand, CSM does not consider many basic functions of a process equipment, like lubrication, chip removal, tool changing and so on, which can often dominate the energy requirements, see [30].

The potentialities of CSM have been tested on the pallet transport line of a real de-manufacturing pilot plant [32,33], where the main energy consumption is due to the activation of the actuators moving the pallet from a transport module to an adjacent one. In order to implement and validate CSM in the considered test case, a Dynamic Control Platform for Industrial Plants (DCPIP), based on the C++ object oriented programming language, has been designed. Then, the pallet transport line has been modeled into the SIMIO DES platform [34] interfaced to the DCPIP. Finally, the DCPIP has been connected to the pilot plant itself and the measured power effectively absorbed by the system has been compared to the value computed in simulation. The results achieved show that CSM is able to provide an accurate prediction of the power absorbed by the transport line and of the overall energy consumption of the system.

The paper is organized as follows. The CSM basic concepts are described in Section 'The CSM energy consumption methodology'. Section 'The application of CSM to a de-manufacturing plant' is devoted to describe its application to the transport line of the de-manufacturing plant. Specifically, the structure and behavior of the system are first described and the characterization of its actuators, in terms of absorbed power, is introduced. Then, the structure of the control system is discussed together with the DCPIP characteristics. In Section 'Simulation and experiments results' finally, the simulation and experimental results obtained with CSM are presented and compared. Some conclusions are drawn in Section 'Conclusions', where also the future developments of this research activity are sketched.

The CSM energy consumption methodology

The basic idea of CSM consists of associating a specific power profile to each actuator driven by its logic control action and considered in the DES model of the process equipment. Specifically, CSM can be summarized as follows:

- Assume to have n actuators whose state (switched on/off) can be modified at fixed and synchronous time intervals Δt. Usually Δt also corresponds to the adopted simulation step time.
- Letting t be the continuous-time index, for each actuator define by $Act_i(t)$ the Boolean control variable corresponding to the activation/deactivation command, i.e. $Act_i(t) = 1$ if the ith actuator is working at time t while $Act_i(t) = 0$ if the actuator is in idle.
- Denote by $PAct_i$ the (known) absorbed power of the ith actuator in working conditions. For simplicity we consider here $PAct_i$ as constant, although this assumption could be easily relaxed to consider time varying power profiles or modulating control actions.
- Compute the instantaneous absorbed power of the ith actuator at time t as

$$PT_i(t) = PAct_i \cdot Act_i(t) \quad (1)$$

and the total absorbed power as

$$PT(t) = \sum_{i=1}^{n} PT_i(t) \quad (2)$$

- Compute the total energy consumption at any time $t = k\Delta t + \tau$, $k = 0, 1, 2, \ldots$, with τ belonging to the interval $[0,\Delta t)$, as

$$E(k\Delta t + \tau) = E(k\Delta t) + PT(k\Delta t)\tau \quad (3)$$

Concerning this procedure, some remarks are in order. First, from Eq. (2) it is apparent that small size actuators can be neglected, with significant advantages in terms of modeling effort. However, some care must be placed in removing actuators which, although characterized by a small instantaneous absorbed power, remain active for long periods of time. In fact, their contribution to the total energy consumption could be significant, as apparent from the integral nature of Eq. (3).

A second consideration concerns the power profile $PAct_i$. As already noted, and extensively discussed in [10], the machine absorbed power profile depends on many factors, such as the specific operating machine technology, the material to be machined and the product to be produced in terms of machining process. Therefore, it would be useful to design a software data structure able to set the most suitable instantaneous power value to be assigned to $PAct_i$ at each simulation step. In this regard, nominal data taken from the technical datasheets, or measured from the field, can be used, see [25].

In general, compared to the approaches requiring the definition of the energy states of the process equipment, CSM is simpler, since the description of the control behavior is often already available from the control engineers who design the control system. In addition, as clearly expressed by Eqs. (1) and (2), the estimate of the maximum power peak is immediate. This implies that, in case of modified control sequences, there is no need to re-analyze the system from the point of view of new energy states, which in turn would require additional field measurements and the power profile reformulation. This is very important in the industrial production process design to guarantee flexibility to the plant designer and to the control engineers. Indeed, with CSM it is easy to design and simulate the process plant, and then to evaluate the total absorbed power maximum peak according to the defined plant control policy. In addition, it is possible to modify the plant layout and the control system functionalities in order to limit the plant power requirements, so obtaining significant savings in the production system costs both in terms of electrical power supply infrastructure and of energy purchasing [31].

The application of CSM to a de-manufacturing plant

The de-manufacturing pilot plant considered for the validation of the CSM approach, shown in Fig. 1, is located in the laboratory of