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A control oriented model for manual-pick warehouses

Francesco Basile*, Pasquale Chiacchio, Domenico Del Grosso

Dipartimento di Ingegneria Elettronica e Ingegneria Informatica, Università di Salerno, Italy

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ABSTRACT

Nowadays the low cost of wireless communications allows the real time monitoring of the state of manual-pick warehouse systems making possible the real time control of these systems. At this aim, an approach based on a two-level model is presented in this paper. At the lower level, Petri nets are used to build online a model representing the active missions state and to detect conflicts among resources. At the upper level, logical expressions are used to add constraints for a single mission or item. The model is proved to be effective for online monitoring, scheduling and rescheduling of warehouse activities.

1. Introduction

Distribution Centers (DCs) are a key component of supply chains. The activities within a DC include the receipt of items and customer orders, storing items, order picking, shipping, customer service and reclamation. The picking activity is a critical activity of DCs. Indeed, these DCs consist of big warehouses which are usually not automated since they store too many different items: it is required to pick up a pallet as well as a single item like a cellular phone or a lamp. Furthermore, in a manual-pick warehouse the system configuration is extremely variable during the system running and the input of modern DCs is highly unpredictable: for example, a picker may decide to stop autonomously; agents' performance are not fixed since the maximum weight they can carry is variable; the items to be stored/picked are carried by trucks whose time arrival is variable. For these systems it is also required a frequent rescheduling of activities to ensure a certain level of performance as they depend on the picker current load, on the occurrence of delays, etc. The rescheduling should be done when an event occurs (a new order arrives, agent stopping, etc.), and also when the system performance is different from the expected one, if a monitoring of the activities is implemented.

The objectives are to minimize the time to complete a set of missions or the picker's idle time by reducing travel distances and delays as well as to maintain the balance of load among the pickers. It is usual to approach the problem using heuristics to achieve good schedules quickly for realistically sized problems. The control of these systems can be classified as a simulation optimization problem since the objective function and/or some constraints are responses that can only be evaluated by computer simulation (Azadivar, 1999), being these functions implicit functions of control inputs of the system.

A lot of results are available for unit-load automated storage systems, while few results are available for other storage systems (Gu, Goetschalckx, & McGinnis, 2010; Rouwenhorst et al., 2000). Recently, the travel time estimation, the order-picking strategies and the problem of storage assignment in manual-pick warehouses have been studied in Parikh and Meller (2010), Parikh and Meller (2008), and Chan and Chan (2011) respectively. With respect to the automated warehouses, the control of the manual-pick ones is not affected by deadlock issue. More precisely, this issue can be neglected since person-onboard vehicles and agents are not stopped for example when they are required to complete a mission but they cannot. If it is required to pick up a load when there is no space in the bag, agents go back to the home position, they empty the basket and continue their missions list: in this case a deadlock does not occur, while in automated warehouses the same situation produces a deadlock.

Nowadays the low cost of wireless communications allows the real time monitoring of the state of manual-pick warehouse systems (e.g. the position of picker agents, person-onboard vehicles) or at least to know in real time when a manual picking/storage operation is completed. Then, the real time control of these systems at a reasonable cost is possible.

The contribution of this paper is proposing a new control oriented model which can be used for online monitoring, scheduling, rescheduling of activities by using simulation. The model proposed in this work seems to be promising for this kind of applications since, it is modular, scalable and it is built online by associating a Petri Net module to each active mission and to each

* Corresponding author. Tel.: +39 089964400; fax: +39 06233227957.
E-mail address: fbasile@unisa.it (F. Basile).

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available agent. This allows to represent by the net places the phases of a mission as well as the state of each resource. This model can be implemented online at low-cost. The availability of the current state of the activities allows the rescheduling from the current system state as well as the evaluation of the discrepancy between the actual performance from the expected one.

The motivation of using a formal model like PN modules is the local state representation: each activity is modeled by a transition that is graphically connected to a place that models a resource state. This allows to detect easily conflicts, whose resolution is the key problem for the control of these systems. The use of colors allows to take into account the fact that the travel time to pick up a certain item depends not only on the distance of storage location from the actual resource position but also on the type of resource. Any travel time model can be integrated with the proposed model. Moreover, a formal model permits to formally characterize the system's state to realize halt and recover mechanisms so that the state of the system at a certain time as well as the simulation outputs are saved and restored when necessary.

Furthermore, in a manual-pick warehouse, where different kinds of items are stored, the set of constraints is very large and it is not easy to represent them using general mathematical expressions since they are very specific to a certain resource, item, and so on. To overcome this problem, an additional model level, called *auxiliary process* (AP), is used where by means of logical expressions it is possible to add constraints also for a single item or mission. This level is implemented by a set of logical expressions which depend on the formal model state. Such constraints reduce the number of conflicts that are solved by the online schedule (re-schedule). Thus, AP reduces the customization efforts for the control of manual-pick warehouse systems since it allows to write state-dependent constraints by using a standard formalism.

Finally, simulation schemes are presented to implement a dispatching rule based control for these systems. These simulation schemes are obtained extending the classical scheme for the simulation of discrete event systems based on the scheduled events list (Cassandras & Lafortune, 2008). These schemes are immediately implementable in standard programming languages by themselves, and efficient techniques have been proposed in the literature (Cassandras & Lafortune, 2008) to speed-up these simulations avoiding the use of commercial software. Simulation results and hardware setup show the effectiveness of the approach.

2. Related literature

In this section, papers about the use of formal models, dispatching rules and simulation in warehouse systems or manufacturing systems are discussed since these concepts are widely adopted in the paper.

The importance of formal methods for modeling and controller synthesis in manufacturing systems context is a well addressed topic in the literature. Several authors used Petri Nets (PNs) or timed PNs (TPNs) and, to obtain a more compact model, they used colored PNs (CPNs) or Colored Timed PNs (CTPNs) (Amato, Basile, Carbone, & Chiacchio, 2005; Basile, Chiacchio, & Teta, 2012; Dotoli & Fanti, 2004, 2005; Koh & Di Cesare, 1991; Ramaswamy, Valavanis, & Landry, 1992; Valavanis, Ramaswamy, & Landry, 1994; Zhang, Freiheit, & Yang, 2005). In the modeling phase PNs can be also used together with object-oriented techniques (Basile, Chiacchio, & Del Grosso, 2009). CTPN models can be easily implemented on industrial controllers as shown in Basile and Chiacchio (2007). Furthermore, PN models allows the application of online fault diagnosis techniques (Basile, Chiacchio, & De Tommasi, 2012) as well as the synthesis of efficient supervisory control laws (Basile, Chiacchio, & Carbone, 2007; Basile, Chiacchio, & Giua, 2007).

Having an automated model generation methodology (Son, Wysk, & Jones, 2003) is very important for the real-time control of manufacturing systems, especially for reconfiguration purposes. At this aim, PNs can be a good formal method as shown in Li, Dai, and Meng (2009) where a PN supervisory controller is proposed for manufacturing systems, which can be easily reconfigured in order to react to the perturbations. Among formal modeling methodologies, an appealing approach is the matrix-based framework proposed by Tacconi and Lewis (1997). Application to warehouse systems can be found in Giordano, Zhang, Naso, and Lewis (2008) where a variable dispatching rule control approach is used for operational control issues. In the same paper it is shown that the matrix-based model can be included into a multilevel control architecture where the model is used to determine when a control decision has to be made from upper levels, and to feature operational control tasks too. Simulation is used to tune, off-line, some parameters of the control law.

The use of dispatching rules is a frequent control solution for the real-time control of manufacturing systems in general (Ho & Liu, 2006; Jeong & Kim, 1998; Kim & Kim, 1994; Vis, 2002). A combination of simple dispatching rules outperforms a fixed dispatching rule (Wu & Wysk, 1989). Such a combination can be implemented by means of a simulation-based mechanism for the online control. Jeong and Kim (1998) propose a systematic framework for the real-time control in manufacturing systems using simulation and dispatching rules. In Church and Uzsoy (1992) it is demonstrated, through analytical results, that event-driven policies produce better schedules than periodic rescheduling policies.

In Giordano et al. (2008) an appealing formal model is devised for warehouse systems. The simulation of the model is not used to test in advance the effects of a control policy, over a certain time horizon, but to off-line tune the parameters of an objective function. Previous works as Son et al. (2003) use simulation based control usually exploiting commercial simulation tools like Arena© instead of formal models. Then, these approaches are not enough general to be applied to every warehouse systems and online automated model generation. CTPNs are used in this paper to model system activities while in Amato et al. (2005) and Dotoli and Fanti (2004) they are used to model physical layout. Moreover, the model is here automatically generated and rebuilt when changes occur in the system.

3. Problem statement

In a manual-pick warehouse there are several parts, or items, to be moved and resources that can execute movement tasks, called *missions*. The basic control problem consists in determining which mission must be executed by available resources, in order to obtain the best mission-to-resource assignments over a certain time horizon.

In the systems considered in this work the parts to be handled can be *unit loads*, i.e. parts that cannot share the resource with other parts in the same travel or *less than unit loads* (LTUL) (Malmborg, 1998), i.e. parts that can be handled at the same time by a resource, since they fill only a portion of the resource.

Missions are supposed to be contained into a *buffer* which can be refilled whenever a new batch of missions becomes available. Typically, the arrival of missions in a manual-pick DC is totally asynchronous and random.

Resources can be human pickers or person-onboard vehicles. They can:

- belong to disjointed compatibility groups (Fig. 1a): not every resource, indeed, is necessarily able to execute every mission (for example a fork-lift truck cannot handle small objects);