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A distributed multi-agent production planning and scheduling framework for mobile robots ☆

Stefano Giordani [a,*], Marin Lujak [b], Francesco Martinelli [c]

[a] Dipartimento di Ingegneria dell'Impresa, Università di Roma "Tor Vergata", Via del Politecnico 1, 00133 Roma, Italy
[b] University Rey Juan Carlos, CETINIA, Calle Tulipan s/n, 28933 Móstoles, Madrid, Spain
[c] Dipartimento di Informatica, Sistemi e Produzione, Università di Roma "Tor Vergata", Via del Politecnico 1, 00133 Roma, Italy

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ABSTRACT

Inspired by the new achievements in mobile robotics having as a result mobile robots able to execute different production tasks, we consider a factory producing a set of distinct products via or with the additional help of mobile robots. This particularly flexible layout requires the definition and the solution of a complex planning and scheduling problem. In order to minimize production costs, dynamic determination of the number of robots for each production task and the individual robot allocation are needed. We propose a solution in terms of a two-level decentralized Multi-Agent System (MAS) framework: at the first, production planning level, agents are tasks which compete for robots (resources at this level); at the second, scheduling level, agents are robots which reallocate themselves among different tasks to satisfy the requests coming from the first level. An iterative auction based negotiation protocol is used at the first level while the second level solves a Multi-Robot Task Allocation (MRTA) problem through a distributed version of the Hungarian Method. A comparison of the results with a centralized approach is presented.

1. Introduction

An external demand of a manufacturing system is generally a fluctuating stochastic process, usually known with a satisfactory accuracy only over a limited time horizon ahead. This introduces, at the strategic level, a high degree of uncertainty in the design of a production system and a supply chain where critical decisions must be taken based on aggregate and approximate information (see, e.g., Mun, 2002).

In traditional shop-floor planning, establishing a production facility requires the selection of static production machines and robot manipulators which would be suitable for long term production plans. With the advances in the development of mobile production resources, now it is possible for many products, once manufactured only by large production machines permanently tied to single locations, to be manufactured with smaller, mobile robots. One of the first such robots was presented in July 2010 by robotic producer Kuka (Bischoff et al., 2010). The shop floor layout with mobile robots makes the strategic decisions less critical with respect to the ones associated to the design of a plant where machines (i.e., production resources) are located on static positions. A dynamic layout represents in fact a less constrained facility where design decisions are postponed to the operative level and become reversible options. Furthermore, it is more effective in responding to a fluctuating external demand and can be considered, for this reason, in the same vein as other solutions adopted through the years in the manufacturing domain for the same purpose, like, among others, Flexible Manufacturing Systems (e.g., Huang and Chen, 1986), Group Technology (see, e.g., Selim et al., 1998), Holonic Manufacturing (see, e.g., Christensen, 1994), and Agile Production Systems (see, e.g., Dugnay et al., 1997).

The high degree of flexibility achieved by the proposed dynamic multi-robot layout leads to a more complex operation management which may render centralized architectures unviable. Centralized architectures in such complex environments are often impractical because of computational and communication bottleneck and the vulnerability of system failure. On the other hand, a bottom-up multi-agent modular architecture distributes computational resources and capabilities among the agents and does not suffer from the "critical point of failure" problem associated with centralized systems (see, e.g., Wooldridge, 2002). Further advantages of a decentralized multi-agent approach are modularity, decentralized knowledge bases, fault-tolerance, redundancy and extendibility, in the sense that new robots can be added to the original system without any change in the system architecture (see, e.g., Lueth and Laengle, 1994).

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* Corresponding author. Tel.: +39 06 72597358; fax: +39 06 72597305.
E-mail addresses: stefano.giordani@uniroma2.it (S. Giordani), lujak@ia.urjc.es (M. Lujak), martinelli@disp.uniroma2.it (F. Martinelli).

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For all the above reasons and because mobile robots are autonomous entities with limited vision and communication capacities, in this paper we propose a decentralized two-level Multi-Agent System (MAS) framework for the case where the production is executed exclusively or with the additional help of mobile robots, as shown, e.g., by Helms et al. (2002) and Tan et al. (2009). On the first, production planning level, tasks compete for the mobile resources (robots) required for their execution. Assuming that the planning time horizon is subdivided into a finite number of time periods, the objective of the production planning level is the determination of the number of the robots to be assigned in each time period to the tasks. This is done in order to minimize the total production cost for each task (with the products' demand known over all the time periods in the given time horizon). The resulting problem is a multiple decision maker multi-item dynamic lot-sizing problem with limited production capacity (e.g., see Jans and Degraeve, 2008). The problem is NP-hard since it can be shown to generalize the very special case with single-decision maker, single-item, zero inventory holding cost, convex production cost function, unit set-up cost, and no production capacity, that has been proved to be NP-hard by Florian et al. (1980). Since the problem at production planning level is NP-hard this level of the MAS framework is coupled with a heuristic iterative auction based negotiation protocol to coordinate the agents' decisions (see, e.g.: Kutanoglu and Wu, 2006; Roundy et al., 1991; Schneider et al., 2005). The resource prices, needed for the iterative auction based protocol, are updated using a strategy inspired by the subgradient technique used in the Lagrangian relaxation approach (see, e.g., Barahona and Anbil, 2000; Chen et al., 1998).

Given the number of robots assigned to the tasks in each time period according to the decisions made at the first, planning level, on the second, scheduling level, the objective is to minimize the total distance covered by the robots in the reallocation between consecutive periods. Therefore, a Multi-Robot Task Allocation (MRTA) problem is solved for each period. The objective of the MRTA problem is to find the assignment of n robots to a set of n tasks (target positions) based on the optimization of some global objective function (see, e.g., Gerkey & Mataric, 2003). We assume that the decision making environment for this level is decentralized as well, with as many decision makers (agents) as there are the robots in the system. In particular, we assume robots to be collaborative, homogeneous, arranged in regular networks and relying on local communication only between neighboring robots. We use a distributed version of the Hungarian Method for this allocation problem, a distributed combinatorial optimization algorithm which solves the assignment problem in strongly polynomial time (Giordani, Lujak, & Martinelli, 2010).

Note that the problem definition and the proposed modeling framework are general enough so that the production planning and scheduling problem and the solution model can be applied also to other types of mobile manufacturing resources and production operators.

We experiment the proposed model considering a fluctuating demand modeled through an ARMA process. To measure the effectiveness of the approach, the social welfare (see, e.g., Chevaleyre et al., 2006) of the task agents in the decentralized scenario is compared with the performance obtained through a centralized solution. Preliminary results regarding the first level of the proposed framework have been presented by Giordani et al. (2009) where the problem addressed on the second level (the robot movement) was not considered. The integrated solution of the two levels is a viable solution for the incorporation of mobile robots on the shop-floor and provides indeed an interesting insight into the problem. In particular, we show that the decentralized approach of the first level gives comparable results to the centralized one while the required total movement distance of the robots' reallocation is in general inferior.

The remainder of the paper is organized as follows. We introduce related work and review some of the economic models used in MAS negotiation for resource allocation in Section 2. In Section 3, the decentralized production scheduling problem is presented. The two-level solution approach is given in Section 4. In Section 5, we present the simulation results. We close the paper with the conclusions in Section 6.

2. Related work

There is a vast literature on planning and scheduling techniques in manufacturing based on multi-agent systems (see, e.g., Shen et al., 2006, 2007; Wang et al., 2008). For multi-agent interaction and negotiation, there are several applicable economic models which might work well for the production planning level of the presented framework where tasks compete for resources (robots): commodity market, posted price, bargaining, tender/contract-net, and auction model (see, e.g., Buyya et al., 2002; Chevaleyre et al., 2006; Kraus, 2001), which is the approach chosen in this paper.

Regarding the second level, MRTA corresponds to the (linear sum) assignment problem for which the first developed algorithm was the Hungarian Method (Kuhn, 1955). The Hungarian Method or Kuhn–Munkres algorithm is a well known iterative algorithm which maintains dual feasibility during calculation and searches for a primal solution satisfying complementary slackness conditions. If the primal solution is feasible, the solution is optimal. If the primal solution is not feasible, the method performs a modification of the dual feasible solution after which a new iteration starts. Hungarian Method can be implemented using the alternating trees so that its worst case time complexity is limited by $O(n^3)$ (see, e.g., Papadimitriou and Steiglitz, 1982).

There are several main approaches to the assignment problem (see, e.g., Burkard and Çela, 1999). The classical centralized assignment methods find a solution through the iterative improvement of some cost function: in primal simplex methods it is a primal cost, and in Hungarian, dual simplex and relaxation methods it is a dual cost (see, e.g., Bertsekas, 1992).

The Auction algorithms can improve as well as worsen both the primal and the dual cost through the intermediate iterations, although at the end, the optimal assignment is found (Bertsekas, 1991). Bertsekas in this work introduces the auction algorithm in which the agents bid for the tasks in iterative manner, and in each iteration, the bidding increment is always at least equal to ϵ (ϵ-complementary slackness). If $\epsilon < \frac{1}{n}$ the algorithm finds the optimal solution, and it runs in $O(n^3 \cdot \max\{c_{ij}\})$ time, where c_{ij} is the assignment cost of robot i to task j, that is in pseudo-polynomial time. Using ϵ-scaling technique and appropriate data structures a polynomial time version of the auction algorithm running in $O(n^3 \log (n \cdot \max\{c_{ij}\}))$ time is given by Bertsekas and Castanon (1989) and Bertsekas (1992).

Zavlanos et al. (2008) provide a distributed version of the auction algorithm proposed by Bertsekas for the networked systems with the lack of global information due to the limited communication capabilities of the agents. Updated prices, necessary for accurate bidding can be obtained in a multi-hop fashion only by local exchange of information between adjacent agents. No shared memory is available and the agents are required to store locally all the pricing information. This approach calculates the optimal solution in $O(\Delta \cdot n^3 \cdot \max\{c_{ij}\})$ time, with $\Delta \leqslant n-1$ being the maximum network diameter of the communication network.

There are also many parallel algorithms based on the Hungarian Method. For a good survey see, e.g., Burkard and Çela (1999), and Bertsekas et al. (1995). Among the most efficient parallel algorithms for the assignment problem is the one proposed by Orlin