Holonic Adaptive Production Control Systems

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Abstract - Manufacturing systems are a stochastic, dynamic environment, with new jobs arriving continuously to the system, certain resources becoming unavailable and additional resources introduced. In order to support this particular environment in distributed manufacturing it is necessary to introduce new mechanisms to implement dynamic, distributed scheduling, specially to face disturbances. This paper presents an overview of the manufacturing scheduling problem and some techniques available to handle it. To solve the problem of stochastic, dynamic reaction to disturbances an adaptive control approach is described, based in the holonic manufacturing paradigm and the autonomy degree concept, which each operational holon uses to allow the balance between competition and cooperation.

I. INTRODUCTION

Manufacturing systems are a complex, stochastic and dynamic environment, with new jobs arriving continuously to the system, certain resources becoming unavailable and additional resources introduced.

Traditionally, manufacturing scheduling is elaborated in a centralised manner, often calculated off-line. From the optimisation science research, several techniques were developed and some of them introduced for the manufacturing scheduling problem.

The occurrence of disturbances requires that the schedule is adapted to the new situation as fast as possible. The re-schedule may be done in a short amount of time, to avoid the risk of degradation of the production productivity. In order to support this particular environment in distributed manufacturing it is necessary to introduce new mechanisms to implement the dynamic and distributed scheduling, specially to assure the reaction to disturbances.

The holonic and agent-based approaches present characteristics that support efficiently the development of new manufacturing control approaches, based in autonomous and cooperative entities. The proposed adaptive control approach uses the autonomy degree and to make possible the introduction of dynamic re-configuration in the control approach. The reaction to disturbances is implemented through a change in the control architecture from a hierarchical approach to a heterarchical approach.

The dissemination of the need for re-configuration is crucial in the system self-organisation and in the proposed approach is performed by pheromone-like mechanisms.

II. MANUFACTURING SCHEDULING

Scheduling is one of the main functions performed by a manufacturing control system.

A. Manufacturing Scheduling Problem

Scheduling is the allocation, over the time, of shared resources to jobs, where these assignments must obey to a set of constraints that reflect the temporal relationships between jobs and the capacity limitations of the shared resources [1]. The assignments also affect the optimality of a schedule with respect to criteria such as cost, tardiness, or throughput.

The manufacturing scheduling is a complex combinatorial problem, particularly when it takes place in an open, distributed and dynamic environment ($J!^M$ scheduling sequences, where J is the number of jobs and M the number of machines). For example, in the case of one machine to process four jobs, there are $4!$ (24) possible sequences, but if the number of jobs to process increases to 10, the number of possible sequences will be $10!$ (3628800), being harder to find the best sequence. The problem becomes even harder if instead of one machine, the problem comprises two different machines, where there will be $10!^2$ ($1,3168 \cdot 10^{13}$) possible sequences.

Moreover, the scheduling problem was considered to be static and deterministic. However, the industrial manufacturing scheduling is a dynamic environment, with new jobs arriving continuously to the system, certain resources becoming unavailable and additional resources introduced. So, the schedule needs to be continuously adapted to the new situation as fast as possible.

B. Manufacturing Scheduling Techniques

The scheduling problem has been widely studied in the literature, mainly due to its highly combinatorial aspects, its dynamic nature and its applicability in manufacturing systems [2]. Some referenced methods are the heuristics, constraint satisfaction techniques, neighbourhood search techniques, genetic algorithms, etc.

For simple and small scheduling problems, mathematical programming, such as linear programming, is applied to find the optimal solution. Those algorithms may require a huge amount of time to achieve the optimal solution, and are not adequate to problems with large dimension and complexity.

Since the experience shows that is not important to have the best solution but a satisfactory solution, there are scheduling heuristics, such as EDD (Earliest Due Date) and SPT (Shortest Processing Time), which allow a good approach to the ideal solution, in a shorter period of time. However, the heuristics are not adequate to systematically improve the generated schedules.

The Constraint Satisfaction approach is based in AI (Artificial Intelligent) techniques, formulating the problem with constraints, which is quite analogous to mathematical programming, and using an appropriate constraint programming language [3].

Other approach is based on Lagrangian relaxation. Based on mathematical optimisation techniques, the capacity constraints of a scheduling problem can be relaxed and replaced by a penalty cost. The relaxation of the capacity constraints is quite similar to the mechanism that runs a free-market economy. This approach yields a high performance, but using considerable calculation time [4; 5].

Other researchers use neighbourhood search techniques, which consists in finding, iteratively, a new solution in the neighbourhood of an existing solution. These techniques use for example simulation annealing [6] and taboo search [7] to perform the stochastic search.

Agent technology and holonic approaches has recently been used in an attempt to solve the manufacturing scheduling problem, mainly using algorithms based on previous described centralised techniques, or other distributed behaviour approaches, such as market-based or contract net protocol. Examples of these types of manufacturing scheduling are described in [4; 8; 9].

The introduction of agent technology allows the implementation of distributed scheduling, i.e. the scheduling algorithm is distributed over a number of agents that combine their calculation power and their local knowledge to optimise the global performance [4]. One of the most interesting advantages of the distributed scheduling is the improvement of reaction to disturbances.

III. DISTURBANCE HANDLING

As described in previous points, the manufacturing scheduling is normally elaborated considering a deterministic environment without the presence of disturbances. The occurrence of disturbances leads to a deviation from the initial and optimised plans and degrades the performance of the system due to the machine/system inactivity.

In order to clarify the analysis of proposed dynamic scheduling and control mechanisms for stochastic manufacturing problems, it is important to analyse the possible types of disturbances presented in industrial manufacturing environments.

The main types of disturbances are the manufacturing or work order cancel, the machine failure, the introduction of a new manufacturing order and the layout re-configuration.

Fig. 1. Initial Resource Schedule

To illustrate the disturbance handling problem, let us to

consider the initial schedule, represented by Fig. 1, that comprises several operations to be executed in two resources. This initial schedule will be degraded due to the several types of disturbances, requiring a appropriated re-schedule.

A. Manufacturing or Work Order Cancel

The manufacturing or work order abortion may be due to the cancellation from the customer, a failure that had provoked the destruction of the part, etc. This disturbance causes small impact in the system, because it is only necessary to release the operations already allocated and to re-schedule the other operations in order to optimise the local schedule.

Fig. 2. Work Order Cancel

The modification of the work order attributes, such as the change of temporal window to produce (earliest and due dates), lead to the need to re-schedule all operations.

B. Machine Failure

A machine failure can occur due a tool collision, a broken tool, a mistake in machine program, etc, leading to a temporary or longer out of service of the machine, which becomes unable to accomplish the allocated work orders. The objective is to recover quickly the machine and in parallel to find out alternative solutions to reduce the deviation from the initial plan.

To illustrate the machine failure problem, consider the initial schedule, represented by Fig. 1, and a failure in machine R1 at $t=40s$, being the machine OK after the failure.

This failure will cause a delay in the execution of T1, which affect the start of T2 work order. Additionally, since the machine R1 can take several time to recover from the failure, it is necessary that the work orders allocated to R1 be re-schedule to minimize the deviations. It is possible to have different solutions, the best solutions being those that lead to the shortest deviation from the initial plan. The best solution for this case is to swap K1 and T2 in R2 machine.

Fig. 3. Re-scheduling due to a Machine Failure

Other solutions can be to delay both T2 and K1 operations in R2 machine, which leads to a worst solution because the deviation of manufacturing lead time is bigger, or cancel the work orders T1 if it cannot fulfil the due date.

C. Introduction of a New Manufacturing Order

The introduction of a new manufacturing order, usually with high priority, implies a re-scheduling, trying to insert the manufacturing order in a schedule fulfilling the earliest and due dates.

Consider the introduction of a new manufacturing order, for example the manufacturing order X, that comprises the work orders X1 (10s, ed=20s, dd=35s) and X2 (15s, dd=60s). In this case, it is necessary that work order X1 be introduced in the first empty space found after $t = 20$ s, and the other work orders delayed. In relation to the work order X2, this was introduced in the first empty space after the execution of X1, delaying the work orders T2 and K1.

Fig. 4. Introduction of a new Manufacturing Order

This type of disturbance is only a problem when it leads to temporal conflicts with other already allocated work orders or when it is a priority work order.

D. Layout Re-configuration

The layout re-configuration represents the re-organisation of the manufacturing resources available in the factory plant, such as the addition of a new resource or the removal of a resource. The addition of a resource case causes small impact in the system, because it increases the alternative solutions for the execution of manufacturing order, solving in some cases some conflicts problems.

On the other hand, the removal of a resource leads to a more complex problem, that can introduce conflicts in the system. In this case, the work orders allocated to the removed or unavailable resource should be re-scheduled by the other available resources.

IV. HOLONIC AND MULTI-AGENT APPROACHES

The traditional manufacturing control systems have low capacity to adapt and react to the dynamic changes of its environment, such as the reaction to disturbances and to the market volatility.

The new generation of manufacturing control systems should combine the reaction to the occurrence of disturbances and the optimisation of the global performance of the system. These requirements imply the development of new manufacturing control approaches with more autonomy, agility, intelligence, cooperativeness and robustness against disturbances.

A. Multi-Agent Systems

The multi-agent system paradigm is one approach that

derives from the Distributed Artificial Intelligence, being characterised by decentralization and parallel execution of activities based on autonomous entities, called agents.

The definition of agent concept is neither unique nor consensual, existing some discussion in the scientific community about the issue, such as described in [3; 10; 11]. Despite the some definitions and interpretations for agents, our vision of agent is:

An autonomous component, that represents physical or logical objects in the system, capable to act in order to achieve its goals, and being able to interact with other agents, when it doesn't possess knowledge and skills to reach alone its objectives.

In the automation and manufacturing domain, an agent can represent physical resources, such as tool-machines, robots, auto-guided vehicles and products, and logical objects, such as the scheduler.

A multi-agent system can be defined as a set of agents that represent the objects of a system, capable to interact between themselves, in order to achieve its individual goals. The interaction between agents requires the use of a proper agent communication language.

The agent technology introduces functionalities that support efficiently the distributed manufacturing system needs, such as modularity, decentralization, and dynamic and complex structures characteristics, for what agents are well suitable to solve, and can support efficiently the implementation of holonic manufacturing applications.

B. Holonic Manufacturing Systems

The Holonic Manufacturing System (HMS) is a paradigm that translates to the manufacturing world the concepts developed by Koestler to living organisms and social organizations, mainly that complex systems are hierarchical systems formed by intermediate stable forms, being a part and a whole [12;13]. The word holon is the representation of this hybrid nature, is a combination of the Greek word *holos*, which means *whole*, and the suffix *on*, which means *particle*.

A holon is defined by the HMS consortium [12] as "an autonomous and cooperative building block of a manufacturing system for transforming, transporting, storing and/or validating information and physical objects". The holons that represent physical components comprises a physical part as well as a software part.

A holarchy is defined as a system of holons that can cooperate to achieve a goal or objective. A HMS is a holarchy, which integrates the entire range of manufacturing activities, where key elements, such as machines, products, parts, automated guided-vehicles, etc., have autonomous and cooperative properties. In an HMS, the holon's behaviours and activities are determined through cooperation with other holons, as opposed to being determined by a centralized mechanism.

Another important concept is that a holon can be part of another holon, e.g., a holon can be broken into several others holons, which in turn can be broken into further holons, which allows the reduction of the problem complexity. An example is the representation of a shop floor control system,

which have a holon designed by *Manufacturing Cell Holon*. This holon can be a set of four other holons: *Robot Holon*, *Milling Holon*, *Turning Holon* and *Drill Holon*.

V. ADAPTIVE CONTROL APPROACH

The proposed approach to face the dynamic and agile adaptation to disturbances is based on holonic manufacturing systems paradigm, supported by a set of autonomous and cooperative holons, each holon representing a manufacturing entity, such as a machine-tool, a robot and an order.

The implementation of the holons entities is done using the agent technology, taking advantage of modularity, decentralization, and dynamic and complex structures design features.

A. Factory Entities and Supervisor Role

As in the PROSA architecture [13], the manufacturing holons are grouped into product, task, operational and supervisor holon classes.

The role of the supervision holon, not present in PROSA is inspired in biological systems and introduces coordination and global optimisation in decentralised control approaches. The supervisor holon acts as a coordinator having a global view of its coordination domain, being present in hierarchical organisational control structures, where it represents a shop floor control or a cell controller.

In a heterarchical control approach, the supervisor holon is not present in the system, being the task and operational holons responsible to cooperate, since they have local and partial view of the system.

Fig. 5. Balancing between Hierarchy and Decentralisation

Each operational and supervisor holon integrates scheduling and control mechanisms allowing to have distributed control and scheduling at different hierarchical levels of proposed architecture.

B. Autonomy Factor and Dissemination Concepts

In case of occurrence of disturbances, the system enters into a transitory state, originating the holons re-organisation, according with the autonomy factor and supported by dissemination mechanisms based in pheromone-like techniques.

The autonomy factor, α , is a parameter associated to each operational holon that evolves dynamically in order to adapt its behaviour according its goals and constraints and with the

environment where it is placed. The autonomy factor can be viewed as the balance between the competition and cooperation in the system behaviour, i.e. cooperation for low values of autonomy, accepting the proposals from supervisor holons, and competition for high values of autonomy.

The autonomy factor is a continuous or discrete variable, varying according to some rule. In our case the autonomy factor is implemented using fuzzy logic, represented by the linguistic fuzzy sets {Low, High} and by a fuzzy-rule base, that is kernel for the reaction to disturbances mechanism.

In the stationary state the autonomy factor is {Low}, allowing the operational holon to follow the schedule proposals sent by the supervisor holons. The occurrence of a disturbance may trigger the change of the autonomy factor to {High}.

Fig. 6. Autonomy Factor Model

The occurrence of a disturbance or the perception of a disturbance propagation induces the holon to the need for a system re-organisation, implying the selection of one adequate behaviour, according to the type of disturbance.

The coordination between the holons during the transient state is performed using pheromone-like mechanisms.

The need for re-organisation is disseminated to supervisor holons, through the propagation and deposit of the pheromone to the neighbourhood supervisor holons, as represented in Fig. 7. The holons associated to each supervisor holon receive the need for re-organisation by sensing the pheromone, increases its autonomy factor according with the type of disturbance, and re-organises itself in a heterarchical structure.

Fig. 7. Dissemination of the Need for Re-organisation

After the disturbance recovery, the other holons don't sense anymore the dissemination, reducing their autonomy factor as well, returning the system to the previous structure.

In case of machine break, the operational holon, where the disturbance occurred, maintains the autonomy level, but

registers again in the supervisor holon, since the transient state is already passed.

The dissemination of the re-organisation need using pheromone-like mechanism, allow a dynamic and continuous adaptation of the system to disturbances. The main advantage to use ant-based mechanisms to disseminate the need for re-organisation is to reduce the interaction level and communication overhead between the holons, improving the reaction to the re-organisation.

C. Distributed, Dynamic and Reactive Scheduling

The proposed approach to face the dynamic and stochastic nature of the manufacturing systems is based on dynamic and reactive scheduling supported by a distributed control. The scheduling mechanism does not foresee the stochastic effects, but react to the occurrence of disturbances.

In the stationary state, aiming the global production optimisation, the holons are organised in a federated architecture, with the supervisor holons representing cells and/or shop floor, and having coordination functions through the elaboration of optimised schedule plans for the supervisor and/or operational holons in its coordination domain [14]. The autonomy factor of each operational holon is {Low}, allowing the operational holon to follow the schedule proposals sent by the supervisor holon.

Fig. 8. Re-organisation to React to the Machine Failure

The occurrence of disturbances degrades and deviates the original plans and require an agile and fast reaction, entering the system in a transitory state. In this state the system re-organises itself for a short period of time (τ), with each operational holon adjusting its autonomy factor.

The operational holon which detects the disturbance increases the autonomy factor and disseminates the need for a re-organisation to other holons. In parallel the operational holon re-schedule the operations, interacting with the task holons if necessary to notify the disturbance. Using the example of a machine failure, the operational holon tries to recover locally the failure, by re-scheduling its operations, but if it cannot recover from the failure or it cannot fulfil the due date of an operation, the operational holon increases the autonomy factor, disseminates the need for a re-organisation and according with the type of disturbance selects a appropriate behaviour to handle the disturbance.

According to the disturbance type it is possible to estimate the disturbance recover time (τ), based in previous experience and learning mechanisms. This knowledge will help to forecast the impact of the disturbance in the actual plan and will help to handle the reaction to disturbance.

The other holons that receive the dissemination, also increase their autonomy factor and re-organise themselves in a heterarchical structure. In this structure, and using the example of the machine failure case, the task holons can interact directly with operational holons to re-schedule their operations, achieving a re-schedule plan faster than using the supervisor holon.

After the recovery of disturbance the operational holon should synchronize its schedule with the optimised schedule, notifying the supervisor holon about the new schedule and reducing again its autonomy factor. Since the autonomy factor is reduced, the dissemination of disturbance is finished and the other holons don't sense anymore the occurrence of disturbance, reducing as well their autonomy factor, returning the system to the previous structure.

VI. EXPERIMENTAL RESULTS

Some preliminary experimental tests were executed, aiming at this stage to verify the behaviour of hierarchical and heterarchical control approaches for scenarios with and without disturbances, and the response of adaptive control approach for disturbances scenarios.

A. Scenario Platform

The scenario platform to test the manufacturing control application, comprises the definition of a set of parts to be produced, a set of machines to execute the operations required by the parts, the layout of the machines and the disturbance model.

The physical platform comprises two alternative turning machines, represented by turn-b-Ho and turn-c-Ho operational holons, and a milling machine represented by mach-a-Ho operational holon. The loading/unloading of the milling machine is performed by a robot, represented by robot-a-Ho operational holon. The transport of the parts between the machines, takes 10 seconds, and is executed by an AGV, represented by transp-sys-Ho operational holon.

The shop floor controller is represented by manControl-Ho supervisor holon and intends to coordinate the behaviour of the factory resources.

The disturbance model defines that only the turn-b machine can have failure, with a 15% of probability. In case of failure, the part is destroyed and the time to recover physically is 30 seconds.

B. Evaluation of Hierarchical and Heterarchical Approaches

The first set of tests intent to analyse the behaviour of hierarchical and heterarchical control approaches, comparing the manufacturing lead time and tardiness parameters, for the scenarios with and without disturbances. For each scenario, the experience is executed 6 times, each one providing for each manufacturing order a manufacturing lead time ($mlt_{i,q}$) and a tardiness ($T_{i,q}$). Based in these results it is possible to define average values that characterize the experimental scenario.

The several scenarios were tested for a package of 12 MO (34 operations), the result being illustrated in Fig. 9.

Fig. 9. Evaluation of Hierarchical and Heterarchical Approaches

From the previous results it is possible to verify that in a scenario with no disturbances the hierarchical approach presents better performance than the heterarchical approach, illustrated by the av(/mlt) and av(/T) parameters. However, for scenarios with disturbances the heterarchical approaches presents better performance than the hierarchical approach.

C. Evaluation of Adaptive Control

Related to the introduction of adaptive control, using the same test scenario, it was tested the several control approaches for a package of 6 MO (17 operations). The disturbance model it was slightly modified, having the turn-b machine 100% failure probability. Fig. 10 illustrate the obtained results.

Fig. 10. Evaluation of Adaptive Control

From the results it is possible to verify that in a test scenario with great probability of occurrence of disturbances, the adaptive control approach presents better results than the other control approaches. These preliminary tests are a good indicator to continue the research and development of the adaptive control concept.

VII. CONCLUSIONS

At moment, there is a strong effort in the manufacturing control research in the development of innovative manufacturing control approaches that face the stochastic and dynamic aspects associated to manufacturing environments. Agent-based, and more recently holonic approaches is being used to implement distributed and dynamic scheduling, integrated with the control mechanisms.

The proposed adaptive control approach intends to introduce dynamic re-configuration, to support the agile reaction to disturbances, based in the concept of autonomy degree associated to each operational holon and the supervisor role concept.

The proposed architecture is being implemented using the JADE agent development platform, which is FIPA compliant

and uses Java programming language. The implementation of some decision mechanisms using a rule-based language is done in JESS (Java Expert System Shell).

The initial experimental tests, done on several different scenarios and different control architectures (heterarchical, hierarchical and the proposed adaptive approach), have shown encouraging results.

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