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THROUGHPUT ANALYSIS OF A MULTIROBOT SYSTEM VIA TIMED PETRI NET MODELS

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Abstract: In a multi-robot system (MRS) several robots can operate simultaneously on the same product. We propose to use Timed Petri Nets to evaluate the efficiency of the system The throughput referred to a single robot-platform and a null loading/unloading time allows us to evaluate the benefits of the MRS. A methodology has been developed that, given a set of robots and platforms, allows to decide what the optimum operation mode is (configuration design criteria) under different conditions of operative configuration, number of subtasks, degree of interference, etc. *Copyright © 2002 IFAC*

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1. INTRODUCTION

A multi robot system (MRS) is formed by two or more robots that share a common workspace in a highly coordinated way (Costa, *et al*., 1995). A MRS allows the flexibility and productivity (García, 1996) to be increased, the technical characteristics to be improved (it increases the workload and working area), and makes the accomplishment of complex tasks and the handling of conflicting objects possible.

There are theoretical and technician problems which need to be solved (Bailin, *et al*., 1998; Pérez, 1994). These problems arise from the need to consider a set of entities with a certain degree of autonomy (robots) that have a common objective (production). A global strategy is required, one that contemplates interaction between them, allowing an acceptable degree of efficiency to be reached (Fraile, 1999).

We propose a MRS consisting of three robots and four different working platforms, that allows the characteristics of joint operation to be maintainded even if a robot is out of service, modeled by means of Generalized Stochastic Petri Nets, GSPN (Ajmone-Marsan, 1989; Chiola, 1991; Zimmerman, 1995; Zimmermann and Freiheit, 1998). Diverse configurations of operation have been considered. The different models of the underlying autonomous nets have been analyzed to verify certain desirable characteristics of the system (Silva, 1985): liveness, absence of deadlocks, boundness, etc., which guarantee that the model corresponds to a realistic vision of the system. A parameter have been defined to quantify the interaction between robots and loading/unloading devices to analyze, from a productive point of view, the throughput that can be obtained. An interference factor have been considered to represent the degree of interference between robots in concurrent operations. The methodology followed in the present work is easily applicable to other spatial and operative dispositions of MRSs.

This paper is organized as follows. Section 2 introduces MRS, their basic configurations and operation modes, basic notions of Petri nets, and considers modelling and qualitative analysis of MRS. Section 3 includes performance analysis. Section 4 presents the conclusions.

2. DESCRIPTION AND MODELLING OF THE MRS VIA TIMED PETRI NETS

2.1 Introduction.

The proposed MRS is formed by three robots (R1, R2, and R3) located in the vertices of an equilateral triangle. If robots are close enough an overlapping of the working volumes takes place (Fig. 1).

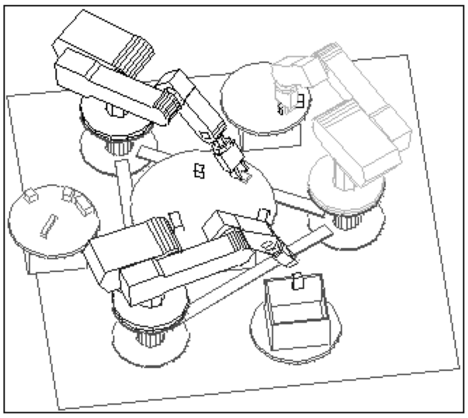

Fig. 1. Muti-robot systems.

Each shared volume is great enough to be able to lodge products and has a physical device that presents the units to produce to the robots. Each one of these volumes has a device which main aim is to settle the pieces in an adequate way so that the operations can be done. These devices are called loading/unloading platforms and will be possible location of the pieces.

The working volume of a robot includes a maximum of three platforms. The performances of each platform depend on its speed rate to the robot. If these present the pieces with relative speed, the robot can always have availability of pieces to work, and there will be no idle times waiting to finish the loading and unloading operations. The cell can simultaneously lodge four units to work.

A MRS with the proposed characteristics in this paper has been developed in the Department of Automatic Control at the ETS of Industrial Engineers of the University of Valladolid. The system is formed by three manipulators (Scorbot ER IX) placed on the vertices of an equilateral triangle. In addition, the system includes a revolving table, a conveyor and three static warehouses.

2.2 Basic configurations.

Multiple configurations can be considered taking into account the availability of robots and/or platforms (González, *et al*., 2001). We consider that robots have the same operation capacities on products so this guarantee their interchangeability (Fig. 2). Also, the four platforms have the same characteristics of loading and unloading pieces.

The nomenclature used to refer to a basic configuration is: ***ijk***, where *i* represents the number of operative robots ($i \in \{1, 2, 3\}$), *j* represents the number of operative platforms ($j \in \{1, 2, 3, 4\}$), and *k* represents the associated particularity of the configurations *ij* in which two alternatives exist ($k \in \{\varnothing, a, b\}$). *k* can be an empty set in those configurations *ij* that do not present any differentiated particularity. The same pair *ij* can have configurations that include a greater or smaller number of common platforms. The distinction between *a* and *b* refers to whether the configuration *ij* includes more or less operative platforms common to robots.

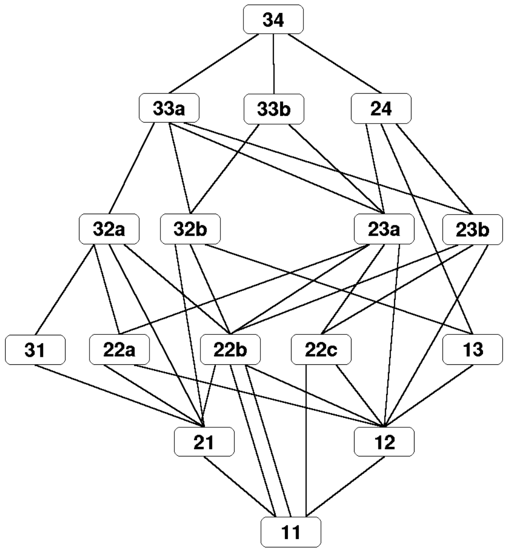

Fig. 2. Basic configurations and their 1-resource relations.

Between the basic configurations a series of transitions related to the addition/elimination of resources (robots and/or platforms) can be considered (Fig. 2). Those transitions have their origin in aspects related to the planning, adaptation of resources, failures, maintenance, addition/elimination of components, etc. For instance, Fig. 3 shows the transition of configuration 34 to 23b caused by the elimination of R2 and P4.

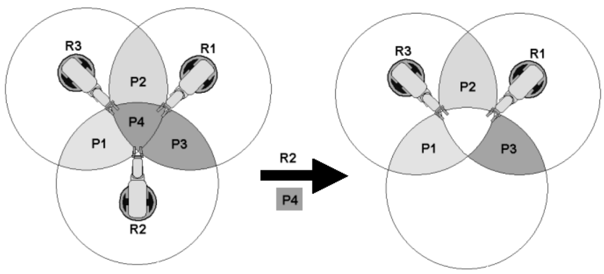

Fig. 3. Configuration 34 to 23b.

In this paper we define *operation* as an atomic activity carried out by a robot on a product situated on a platform. *Task* is the set of operations executed by the robots that are necessary to obtain a finished product in the MRS. A task can be divide into N *subtasks* bringing together atomic operations. Each subtask will be assigned to any robot that has access to the platform holding the product.

Four operation modes have been considered (González, *et al.* 2001):

- Single task. All the operations are assigned to a single robot.
- Sequential subtasks. Each subtask can be done by the same or a different robot, with precedence constraints.
- Parallel subtasks**.** Each subtask can be done by the same or a different robot, without precedence constraints.

- Segmented subtasks**.** Each subtask is also divided in two sequential parts: preparatory and direct actions. It is considered that in the preparatory actions (change of equipment, access to elements of assembly, etc.) interference between robots does not exist and they are necessary for the accomplishment of the direct actions on the products. The direct actions cannot be done in parallel, but those can be done with preparatory actions.

It has been verified the maximum throughput takes place with low number of subtasks of balanced duration (González, *et al*., 2001).

2.3 Timed Petri Nets.

Petri Nets, PN, are a mathematical and graphical formalism (Petri, 1962) which is based on a simple assembly of objects, rules and relations that can represent very complex behaviors. PN can be considered a specially suitable tool for dynamic discrete event systems, DES. In these systems the state changes are related with internal and/or external events, and their typical characteristics include concurrence, asynchronous behavior, nondeterminist selection, mutual exclusion, and real time constraints (Freedman, 1991; Jeng, 1997).

PN is a particular class of directed graph with an initial marking named initial state. There is an extensive biblography related with Petri nets (Girault and Valks, 1998; Murata, 1989; Silva, 1985).

The integration of time considerably changes the behavior of a PN so that many of the properties that are verified for an original net cannot correspond with those of the net with temporary extension. Time can be specified as deterministic or stochastic. A Stochastic Petri Net, SPN (Ajmone-Marsan, 1989), is obtained by associating a variable to each transition that represents the firing delay. The commonest class of SPN is that in which the firing delays follow an exponential distribution: Exponential Stochatic Petri Nets. These nets are isomofics to continuous time Markov chains (CTMC), because the exponential distributions associated to the firing delays do not keep memory from the previous evolution of the system. The Exponential Stochatic Petri Nets have good acceptance due to the availability of software for their automated evaluation. Nevertheless, in many cases the markovian property is not realistic and can produce significant errors in the calculations. The Generalized Stochastic Petri Nets (GSPN) (Chiola, 1991; Zimmermann, *et al*., 1995) incorporate two types of transitions: exponential and immediate. In these nets the immediate transitions have firing priority on the timed transitions that are enabled at a given time. That is the Timed Petri Nets we use in our study.

2.4 Modelling and qualitative properties.

The basic configurations of the MRS have been modeled and qualitatively analyzed by means of PNs, under different operation modes.

In the analysis of the models the desirable qualitative properties have been verified, in particular, liveness and boundness, by means of the calculation of the transition and place invariants. Liveness indicates that the MRS is deadlock free and can evolve independently of the state reached. Boundness implies that all the places of the net have a limit in the number of tokens that can be lodged, which implies that the assigned resources are finite. The simplest configuration of operation is formed by a single robot and a servicing platform. For this configuration, the model by means of PN is the one of figure 4.

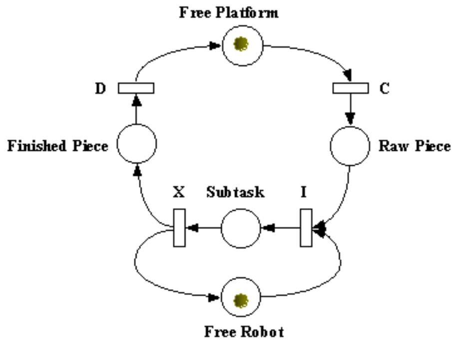

Fig.4. Petri net of the 11 configuration.

Places and transitions of the net can be interpreted as:
Free_Platform: the platform is free and in conditions for carrying out operations on it.
Free_Robot: the robot is free and in conditions for carrying out operations.
C: loading operation in platform. This transition includes both the operation of loading in itself and the availability of pieces to manipulate.
Raw_Piece: place that represents a raw piece on the platform, awaiting the robot to start to performing the tasks.
I (*Init*): this transition represents the starting condition of robot on platform.
Subtask: this represents the allocation of robot to accomplish the pertinent operations on a piece deposited on platform.
X (eXecution): this represents the condition of conclusion of all the operations on the piece deposited on platform, with the consequent liberation of the robot.
Finished_Piece: represents the situation of finished piece placed on platform.
D: transition that includes the task of unloading of the finished piece located in the platform.

In this model, it is considered that all the operations on a piece are done by the same robot (*Subtask* place).

All the places are covered by place invariants, so the net is bounded. The transition invariant (t-invariant) of the net is: *C I X D*. All the transitions are included in the invariant, so the net is alive.

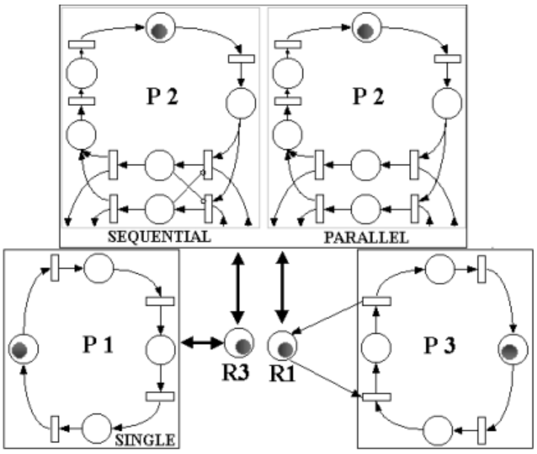

Fig.5. Petri net of the 23b configuration with sequential or parallel mode in the common plarform (P2).

Figure 5 represents the models of the configuration 23b in both sequential or parallel mode in the common platform (P2) and single task in the exclusive platforms (P1 and P3).

3. PERFORMANCE ANALYSIS

3.1 Introduction.

From the dynamic model of the MRS by means of GSPN, the throughput or production rate (pieces produced by time unit) has been evaluated for the different configurations, modes of operation and number of subtasks. Time values are assigned to the different activities (product loading/unloading on platform, duration of the operations be done by robots on products, number of subtasks, etc.) that they allow its influence in the throughput of the system to be considered. The results have been obtained with the tools GreatSPN (Chiola, 1991) and TimeNET (Zimmermann and Freiheit., 1998) executed in Pentium processors under Linux O.S.

3.1 Characteristic parameters.

Given the simplest configuration of operation formed by a robot and a servicing platform (Fig. 4), four basic activities can be defined: (a) *Load of platform j* (C_j) represents the loading time of a piece on platform *j*. (b*) Unload of platform j* (D_j) represents the unloading time of a piece from platform *j*. (c) *Starting of subtask* in platform *j* by robot *i* (I_{ij}) represents the time corresponding to the allocation of robot *i* to a subtask on the piece located in platform *j*. (d) *Execution of subtask* in platform *j* by robot *i* (X_{ij}) represents the time needed to carry out the task on the piece sited on platform *j* by robot *i.*

The random character of the duration of these activities can be related to delays and failures in the platforms and/or robots, etc. Transitions represent the duration of the activities.

The *production time* is defined on a platform *j* by a robot *i* (T_{ij}), adding the durations of the activities of the production cycle: $T_{ij}=C_j+I_{ij}+X_{ij}+D_j$, where $i\in\{1,2,3\}$ and $j\in\{1,2,3,4\}$. Manipulation activities, loading and unloading of pieces on platform, always consume C_j, + X_{ij} + D_j, as opposed to which the starting time, I_{ij}, can be more or less significant. Immediate (I_{ij}=0) and time consuming cases are considered.

The *occupation factor* (β) has been defined as the fraction of the total production time (*T*) in the basic configuration 11 that is dedicated to the manipulation activities on the piece (*X*) by the robots (García, 1996):

$$\beta = \frac{X}{C+I+X+D} = \frac{X}{T}$$

3.2 Reward function: Throughput.

The distribution in the stationary state is the base of the quantitative evaluation of the behavior of the GSPN. On a GSPN model, objective or reward functions on the states of the net can be defined. For each platform, in each configuration and in each operation mode, the *throughput by platform* (η_i), (i.e. pieces produced by time unit in platform *i*) is evaluated. In GSPN models, this throughput is obtained by calculating the quotient between the sojourn time of the token in the place that represents a finished piece in the platform, and the time associated with its unloading transition**.** Also the *throughput by configuration* (η) is evaluated as the sum of the throughputs per platform (η_i) of all the operative platforms in the configuration.

Figures 6 and 7 show the total and relative throughputs based on the occupation factor (β) for the different configurations. When the value of β is small the number of platforms influences the throughput decisively. When the value of β is great the decisive factor is the number of robots involved. For intermediate values there are points of intersection between the efficiency curves of the different configurations that would allow the best configuration to be chosen based on the working point.

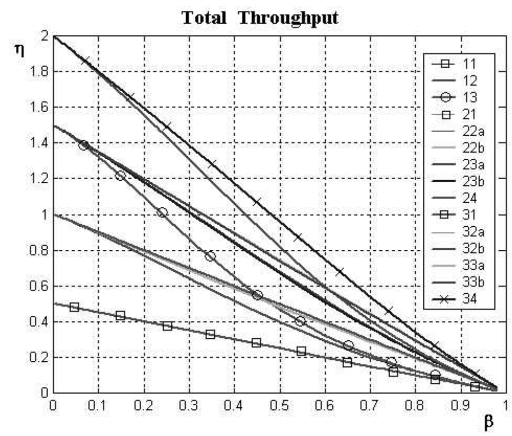

Fig.6. Total throughput. Single task mode.

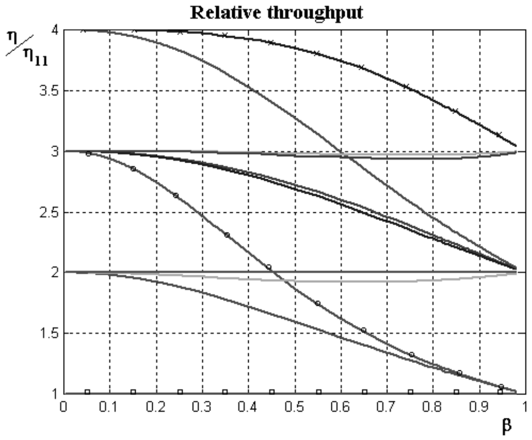

Fig.7. Relative throughput to 11 configuration. Single task mode.

Figure 8 shows the relative throughputs based on the occupation factor (β) for the 23b configuration in segmented and parallel modes. The throughput that can be obtained in the segmented configurations is not intermediate to the equivalent in sequentian and parallel modes. For values of the occupation factor lower than 0.5 it is possible that the throughput has an intermediate behavior between sequential and parallel. For values of the occupation factor higher than 0.7 the throughput decreases, being far lower than even the sequential mode.

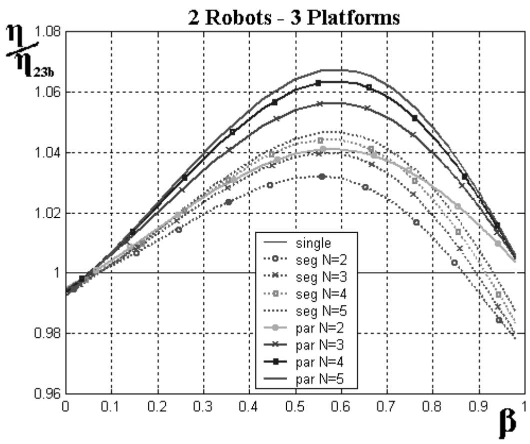

Fig. 8. Relative throughput to 23b configuration. Segmented and parallel modes.

3.3 Interference between robots.

When a platforms is shared by two or more robots it is necessary to consider the necessities of synchronization and the possibility of collisions. In the model an interference factor has been considered (ν) that represents the degree of interference between robots in concurrent operations on a platform in the operation modes which they allow the concurrence (segmented and parallel) on shared platforms.

When several robots works on the same platform, the duration of a subtask due to the interference will be $(1+ \nu)$ times the duration of a subtask without interferences (X/N). If $\nu=0$ would not be interferences between robots, although they are operating on the same platform, and the results would agree the studied ones in the preceding sections.

In this section the effects of the interference are analyzed on the throughput taking like example the configuration formed by two robots and three platforms (23b). These results will be applicable to the rest of the configurations. This configuration has a shared platform and two exclusive to each robot. The division of tasks in the exclusive platforms will not be considered, since it reduces the throughput significantly.

Figures 9 and 10 display relative throughputs based on the occupation (β) and the interference (ν) factors for the 23b configurations and segmented and parallel modes of operation. Throughputs are relative to the 11 (single task) or the 23b ($\nu=0$) configuration. When the occupation factor tends to zero the througput is maximum for all the configurations, and it is the same one independently of the interference parameter because the utilization of robots is minimum. Increasing the occupation factor (β) the influence of the interference (ν) factor reduces throughput quickly.

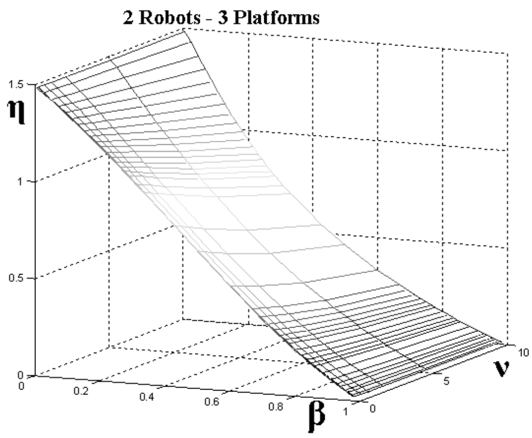

Fig. 9. Relation of throughput (23b configuration) with the occupation (β) and interference (ν) factors in segmented mode.

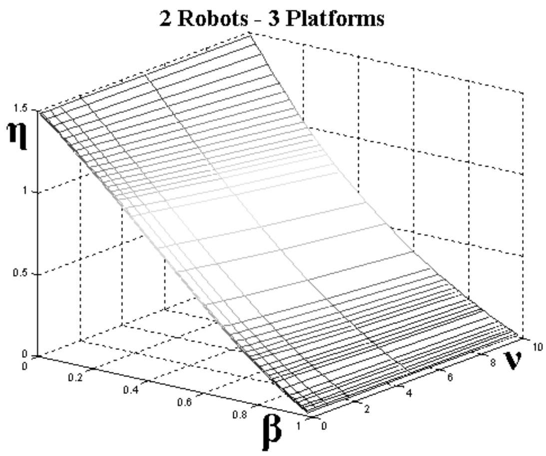

Fig. 10. Relation of throughput (23b configuration) with the occupation (β) and interference (ν) factors in parallel mode.

To obtain the same throughput we can choose between a system without interference but higher occupation factor, or a system with interferences and lower occupation factor, selecting the appropiate subtasks (scheduling and path planning problems).

4. CONCLUDING REMARKS

This paper examines the influence of some parameters on the **throughput** of MRS, in single, sequential, segmented and parallel operation modes. Throughput allows comparisons to be made between the different operative configurations and the modes to carry out the operations on products.

The number and duration of the subtasks influence the throughput. This is maximum with a limited and small number of subtasks of balanced duration. The division of tasks into subtasks in platforms exclusively assigned to a robot diminishes the throughput.

When the value of the occupation factor is small the number of platforms influences the throughput decisively. When the value of the occupation factor is great the decisive factor is the number of robots involved.

For the configurations that execute sequential subtasks the throughput does not differ significantly with respect to the equivalent configurations executed by unique tasks, and it even can be smaller.

The throughput that can be obtained in the segmented configurations is not intermediate to the equivalent in sequentian and parallel modes.

The interference parameter influences negatively in the throughput . This is applicable to any configuration and number of subtasks that are considered in the segmented and parallel modes. Relatively it has more influence in the parallel mode.

Increasing the occupation factor (β) the influence of the interference factor (ν) reduces throughput quickly.

The throughput referred to a single robot with a single platform and a null loading/unloading time allows us to evaluate the benefits of the multi-robot system. Given a set of robots and platforms, decide what the optimum operation mode is (configuration design criteria). Given a set of activities, decide which configuration optimices throughput (subtask sequence design criteria).

The applied methodology has been revealed very useful in the analysis of MRS in our lab and it is possible to be applied in many practical situations to facilitates the decision making, during the work cycle of the system, both in the short and long term.

5. ACKNOWLEDGMENT

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