PROCESSOR REQUIREMENTS FOR RELIABLE AUTOMATED MANUFACTURING ROBOT NETWORKS

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Abstract:

A review is first made of the basic graphs of interest to automated manufacturing using networks of communicating robots. These graphs are then evaluated in terms of relative processor, and processor related hardware, needs for each type of basic robot network to achieve a specified reliability from which relative costs and cost effectiveness results are obtained.

I. Introduction

The requirements of sophisticated microprocessor robots present a good design criterion in automated manufacturing robot network systems. Since manufacturing processes can involve many steps in an industry, and since individual microprocessor robots are generally programmed to carry out these steps, it is important to realize the requirements of processors for each type of robot network [1]. Relative merits of processor-robot networks shall be considered in terms of cost, throughput, reliability, availability, turnaround, development, and complexity. Given the reliability of the robot networks system and the communication links, we can readily compute the reliability/availability of the processor in any given robot network. The reliability of processors will be a major factor in determining the cost-effectiveness of robot networks, and in turn, we believe, a key factor in the requirements of automated manufacturing robot networks. So our major concern in this paper is to evaluate the processor reliability requirements for each type of robot network.

First we present the basic graphs of interest to automated manufacturing using networks of communicating robots [2]. Second we present the general requirements for the robot processor networks. Then detailed analysis for reliability requirements and relative merits are given for linear, star, and ring configurations due to their importance in open production lines, centralized controlled manufacturing, and cyclic production process, respectively.

With the use of similar analysis and techniques the reliability performance evaluation results of the remaining robot networks are presented in figure 3. We use the combinatorial path enumeration technique [3] to evaluate the reliability of the above robot-processor networks. In addition the cost-effectiveness of robot networks is discussed and the summary of reliability expressions, and the cost-effectiveness results of robot networks are presented in Table 1.

II. Basic Graphs of Robot Networks

The basic graphs are those [2] of Fig. 1, as they pertain to robot networks and particularly local manufacturing robot interconnections. In each graph, we represent each distinguished robot-processor in the network by a node and the communications links between nodal entities by a branch.

III. Processor Requirements

In this section we consider a general microprocessor computer and its requirements in a robot-network system. The basic problem in robot-processor networks can be broken into two parts [5]. First the data must be transferred from one processor to another processor. Second, any one processor must be able to exert control over other processors within the system. The data transfer will take place by means of I/O facilities. It may be the result of some calculations carried out upon some other data supplied by all processors or in part by another robot processor in the network system. Also, it can be program instructions where the program from one processor will be loaded from or by another robot processor [5]. An additional requirement is that the appropriate control signals should be present at both the sending and receiving robot processor. An example is give in [7] where data is transfered to a Micro Computer processor at one node which interprets the task description, executes Macro-Commands utilizing position and sensory feedback, and returns final position and sensory status to another Microcomputer processor at a different node of the robot network system. In general, the processors in the robot network system can be classified to have the following primary functions [8]: Coding of Sensory data, Decoding of data coming from another microcomputer, Programmable control, Error detection.

The Requirements for hardware are [6], [8]: Input and output mechanisms designed for real-time processing (eg. data transfer, interrupt control), an optimum instruction set for character sequence handling, high flexibility, i.e. capability of interfacing to different communication links, and terminals, capability of addressing a large memory space, very high availablity, including the capability to configure into a redundant systems.

The Requirements for Software are : Real-time operating system with priority control, capable of handling many tasks concurrently. Software modules for communication control, eg. line control, terminal control, on line test facilities. Dump programs to assist the error recovery conditions. Apart from the hardware and software requirements, some relevant criteria [5] are required to evaluate the performance of processors in the robot network's system.

The following are the most salient performance requirements [5]: (i) Throughput (ii) Memory overhead (iii) Turnaround (iv) Reliability/availability, (v)Maintenance/repair (vi) Relative Cost and (vii) System effectiveness. The first of the above is the throughput (operations per unit time) and is equal to the reciprocal of the time required to execute a set of relevant algorithms. In addition, program length and data storage requirements essential to implement a given algorithm are also of interest. In any robot-processor network a considerable amount of time and memory overhead will be incurred from processor to processor communication. It is this communication and control overhead, which must be minimized for a given application by careful system design. Turn around is another important aspect of multiprocessor-robot systems, particularly when control is to be achieved at one or more local processors. The turn around time must be evaluated against the requirements of true process and it can be expressed in units of time for a given algorithm and system state.

Among the main requirements for considering a robot-multiprocessor system are its reliability/

availability, fault detection, maintenance & repair. It is generally necessary to detect and localize a failure of a processor in any robot network, assuming that the communication links between processors remain intact. Therefore, the requirements of fault-tolerant systems shall arise in a processor system [5]. For example, in the event of an isolated processor failure, such as the shutdown of a processor for maintenace at a particular node of the network, the fault tolerant system must detect the fact that the processor is down and adjust the scheduling accordingly. In order to overcome processor failures, a general reliablity technique is to introduce redundancy in the robot-processor network system, which makes the system more reliable and effective, and of course the cost requirements should be considered for each type of robot network. Next, we will consider in-detail the reliablity/availability requirements for robot processors for the case of linear, ring and star configurations along with the cost-effectiveness of the system.

IV, Reliability/Availability Requirements for Robot Processors and Cost-Effectiveness:

Definition: Reliability of a robot processor is defined[3], as the probability that the processor will operate satisfactorily for a given task within the specified period of time under given operating conditions. In addition, we associate MTBF (Mean Time Between Falures) as the measure of reliablity.

Definition: Availability of a processor is defined[3], as the ratio of the time that the processor system is usable (uptime) to the total amount of time that it is or may be needed. (The total amount of time is the sum of time and the down time for maintenance and repair). Since uptime can be usually the MTBF and the downtime is usually the MTTR(Mean Time To Repair) which is a measure of maintainablity, we can give the expression,

processor availability

$$= \left(\frac{\text{uptime}}{\text{uptime + downtime}} \right) = \left(\frac{\text{MTBF}}{\text{MTBF+MTTR}} \right) \qquad (1)$$

Reliablity analysis: For convenience at this point we assume that the communication links and processors are independent and identically distributed elements (i.i.d). Let p_p be the processor reliability and p_ℓ be the communication link reliability, and P_s be the reliability of the robot network system. Given the network system reliabilty, we wish to calculate the reliability of the processor for each type of robot network. Following the method used for the linear, ring, and star networks, we can compute results for the remaining networks.

1. Linear Network:

Consider a general n-node linear network, Fig. 1a): where $p_1, p_2 \cdots p_n$ represent the robot processors at the nodes $1 \cdots n$ respectively and $\ell_1 \ell_2 \cdots \ell_{n-1}$ represent the communication links between the nodes in the network. Now, the reliability expression can be written as, [here P(·) = reliability probability]

$$P_s = P(p_1 \ell_1 p_2 \ell_2 p_3 \cdots p_{n-1} \ell_{n-1} p_n) \qquad (2)$$

Since $p_1 \cdots p_\ell$ and $\ell_1 \cdots \ell_{n-1}$ are i.i.d. elements, then $P_s = P(p_1)P(\ell_1)P(p_2)P(\ell_2)P(p_3) \cdots P(p_{n-1})P(\ell_{n-1})P(p_n)$. As we are assuming identically distributed elements,

$$P(p_1) = P(p_2) = \cdots = P(p_n) = p_p$$

$$P(\ell_1) = P(\ell_2) = \cdots = P(\ell_{n-1}) = p_\ell$$

We have

$$P_s = p_p^n \, p_\ell^{n-1} \qquad (3)$$

Now, given the network system reliability (P_s) and the communication link reliability (P_ℓ) we can evaluate the reliability of the processor from (3) as:

$$p_p = \left[\frac{P_s}{p_\ell^{n-1}} \right]^{1/n} \qquad (4)$$

In most of the real-life situations, the terms MTBF and availability are more significant for the processor robot networks. If the processor and communication links have constant failure rates λ_p and λ_ℓ respectively, then (3) can be written in terms of these failure rates. Thus,

$$P_s = \prod_{i=1}^{n} e^{-\lambda_{p_i} t} \prod_{i=1}^{n-1} e^{-\lambda_{\ell_i} t}$$

$$= \exp\left[-\sum_{i=1}^{n} \lambda_{p_i} t\right] \exp\left[-\sum_{i=1}^{n-1} \lambda_{\ell_i} t\right] \qquad (5)$$

If λ_s is the system failure rate, then

$$\lambda_s = \sum_{i=1}^{n} \lambda_{p_i} + \sum_{i=1}^{n-1} \lambda_{\ell_i} = \lambda_p + \lambda_L \qquad (6)$$

where λ_p and λ_L are the overall failure rates for the processors and links respectively. Thus, the MTBF of the network system can be expressed as:

$$M_s = \frac{1}{\lambda_s} = \frac{1}{\lambda_p + \lambda_L} = \frac{1}{\sum_{i=1}^{n} \lambda_{p_i} + \sum_{i=1}^{n-1} \lambda_{\ell_i}} \qquad (7)$$

Since the processors and links are assumed as i.i.d. units,

$$\lambda_{p_1} = \lambda_{p_2} = \cdots = \lambda_{p_n} = \lambda_p$$

$$\lambda_{\ell_1} = \lambda_{\ell_2} = \cdots = \lambda_{\ell_{n-1}} = \lambda_\ell$$

we have

$$M_s = \frac{1}{n\lambda_p + (n-1)\lambda_\ell} \qquad (8)$$

where, $\lambda_p = n\lambda_p$ and $\lambda_L = (n-1)\lambda_\ell$. Note that the MTBF of the 'n' processor system (without links) is given by

$$M_p = \frac{1}{n\lambda_p}$$

2. Ring Network: Consider the ring network of Fig. 1b). Since the network is like the linear one with the first and last node identified (3) is replaced by

$$P_s = p_p^n \, p_\ell^n \qquad (9)$$

and the other expressions are similarly modified.

3. Star Network: Consider the Star network of Fig. 1c), the reliability expression for 'n' nodal points is given by the probability of the union of 'n' successful events, i.e.

$P_s = P(A_1 + A_2 + \cdots + A_n)$, where $A_1, A_2, \cdots A_n$ are the 'n' successful paths in the 'n' nodal network. Let us just consider a five nadal processor robot network and compute its reliability. In this case, the reliability expression for a five nodal star network is given by the probability of the union of four sucessful events A_1 to A_4. Thus,

$$P_s = P(A_1 + A_2 + A_3 + A_4) = P(A_1) + P(A_2) + P(A_3) + P(A_4)$$

$$-P(A_1A_2)-P(A_1A_3)-P(A_1A_4)-P(A_2A_3)-P(A_3A_4)-P(A_2A_4)$$
$$+P(A_1A_2A_3)+P(A_2A_3A_4)+P(A_4A_1A_2)+P(A_4A_1A_3)$$
$$-P(A_1A_2A_3A_4). \qquad (10)$$

$$P_s = P(p_2p_1\ell_1)+P(p_1p_3\ell_2)+P(p_1p_4\ell_3)+P(p_1p_5\ell_4)$$
$$-P(p_3p_1p_2\ell_1\ell_2)-P(p_2p_1p_4\ell_1\ell_3)-P(p_5p_1\ell_1p_2\ell_4)$$
$$-P(p_1p_4\ell_2p_3\ell_3)-P(p_1p_5\ell_3p_4\ell_4)-P(p_1p_3\ell_2p_5\ell_4)$$
$$+P(p_4p_1\ell_1p_2\ell_2p_3\ell_3)+P(p_1p_5\ell_2p_3\ell_3p_4\ell_4)$$
$$+P(p_5p_3\ell_4p_1\ell_1p_2\ell_2)+P(p_5p_4\ell_4p_1\ell_1p_2\ell_3)$$
$$-P(p_1p_2p_3p_4p_5\ell_1\ell_2\ell_3\ell_4). \qquad (11)$$

Then, the above expression reduces to

$$P_s = 4p_p^2p_\ell - 6p_p^3p_\ell^2 + 4p_p^4p_\ell^3 - p_p^5p_\ell^4 \qquad (12)$$

Similar calculations can be given for all of the robot network graphs using the technique of [3] with Table I resulting and yielding Figs. 3&4.

To achieve a given robot network system reliability, we see that from Fig. 3, the reliability requirement for the processor is indeed very high for the case of linear, and ring configurations, whereas the reliability requirement is moderate for the case of the star configuration. Similarly, Fig. 4 illustrates the processor reliability requirements for the remaining robot networks. Next we will consider the cost-effectiveness of the robot-processor networks.

Cost-Effectiveness: The most important objective in the design of a robot network is that it be capable of performing its intended function at the lowest total cost, along with high system effectiveness [4]. The major concern in this paper is to show how processor reliability/availability and maintainability enter cost estimates. The processor reliability and maintainability enter cost estimates basically in two ways [9]: I) by determining the overall robot-network system reliability and to acheive a given system effectiveness level, II) by determining the support cost of the robot network system. However, the overall economic evaluation of robot networks requires the consideration of the following in cost analysis [2], [9]: (i) Operating costs, (ii) Research and development costs (iii) Investment costs.

Apart from the above, the overall cost-benefit analysis should also be composed of industrial automated manufacturing requirements, network constraints, and cost-benefit [10].

In order to obtain the cost-effectiveness of robot networks, the most economic method should be chosen, and the present worth should be computed [2], for each processing method for the following parameters, which determine the 'present worth' and 'rate of return',

i = time intervals 0, ···, n

A_i = cost input of the investment

B_i = cost benefit output from the investment

B_i-A_i = operating excess return

γ = rate of interest

Present worth = DCF (Discounted Cash flow) $= \sum_{i=0}^{n} \frac{B_i-A_i}{(1+\gamma)^i}$ (13)

The cash benefit from the investment [11] can only be approximated due to the fact that complete evaluation would not be available for a long period of time, so an approximation is made to the effect that the (B_i-A_i) term in the DCF equation is replaced by α_i[12](cash benefit from investment- cost input to investment or the net cash flow return). Further marketing research is recommended[10], to enable the individual costs assigned to the functional definition of the number of circuit and device components in each robot topology, and in turn the optimal function production costs and possible cash benefits from the investment can also be determined. Then, with these computations completed, the Rate of Return (RE) can be found [2] as:

$$RE = \left[\begin{array}{c}\text{measure of return}\\ \text{(discounted cash flow)}\\ \text{or}\\ \text{operating excess}\end{array}\right] \Big/ \left[\begin{array}{c}\text{invested}\\ \text{capital}\end{array}\right] \qquad (14)$$

A robot network is chosen if the difference in expenditures between the other alternatives and the given one is a maximum (highest internal rate of return =1, and the present worth of cash flow = 0)[2].

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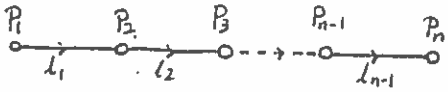
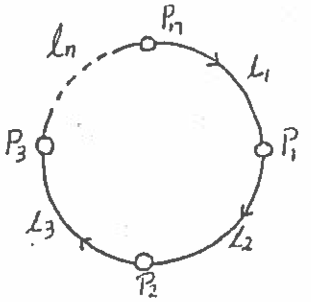
Figure 1. Basic Graphs of Robot Processor Networks

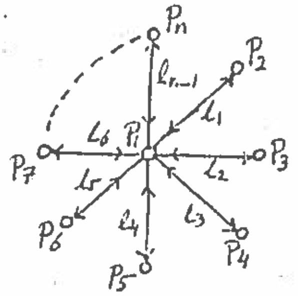
a) Linear



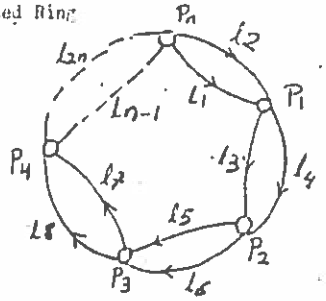
b) Ring



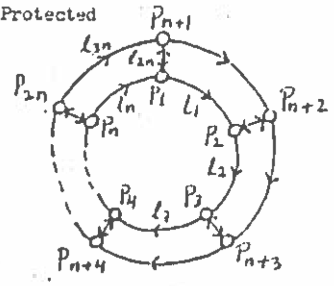
c) Star



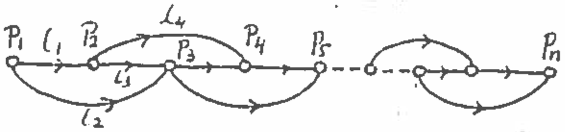
d) Protected Ring



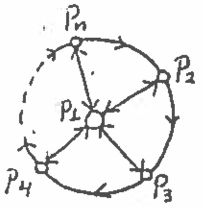
e) Doubly Protected Ring



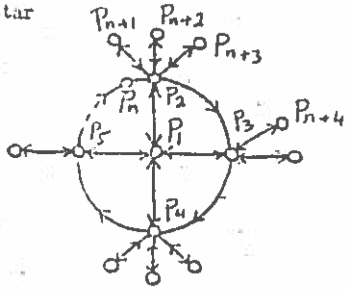
f) Leap Frog



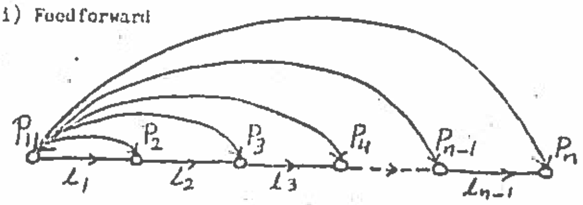
g) Star-Ring



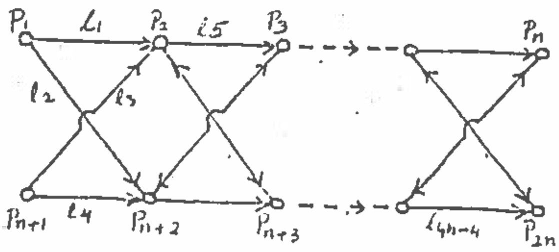
h) Star-Ring-Star



i) Feedforward



j) Lattice



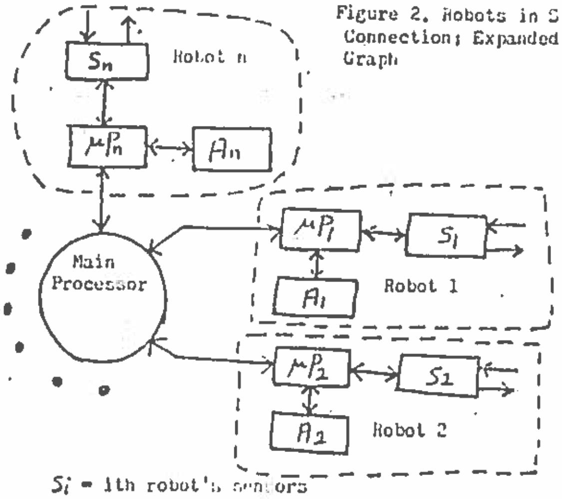


Figure 2. Robots in Star Connection; Expanded Graph

S_i = ith robot's sensors

μP_i = ith robot's microprocessors

A_i = ith robot's actuators

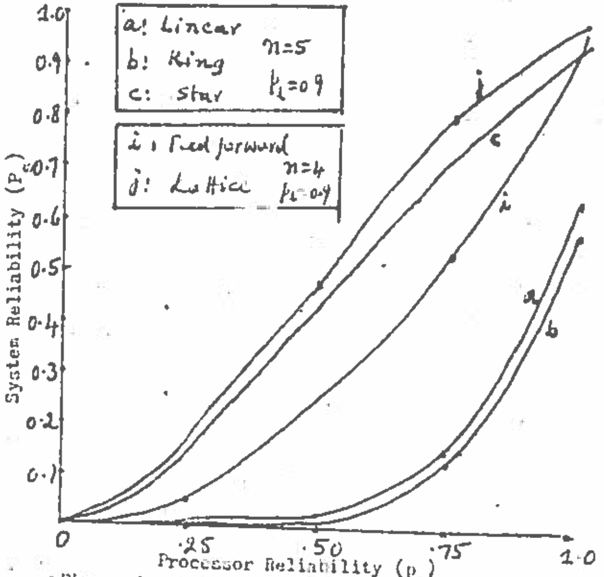


Figure 3. Reliability Evaluation of Ring, Linear, Star, Feedforward, and Lattice Robot Processor Networks

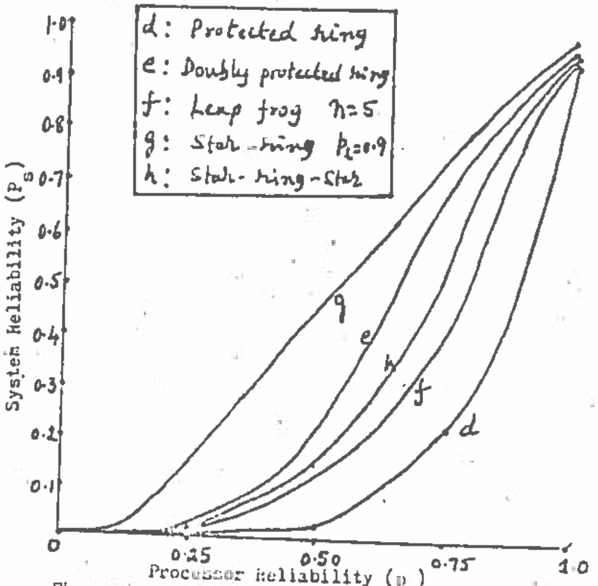


Figure 4. Reliability Evaluation of Protected Ring, Doubly Protected Ring, Leap-Frog, Star-Ring, and Star-Ring-Star Robot Processor Networks

Table I

Reliability Expressions and Relative Cost-Effectiveness Results of Robot Networks:

Robot Network	Reliability Expression (P_s) with P_l = 0.9	Relative Cost-Effectiveness
(a) Linear (n=5)	$P_s = 0.6561\ p_p^5$	Fair
(b) Ring (n=5)	$P_s = 0.5904\ p_p^5$	Fair
(c) Star (n=5)	$P_s = 3.6p_p^2 - 4.86p_p^3 + 2.884p_p^4 - 0.656p_p^5$	Good
(d) Protected-Ring (n=5)	$P_s = 0.95p_p^5$	Medium
(e) Doubly protected Ring (n=5)	$P_s = 0.9509\ [2p_p - p_p^2]^5$	Good
(f) Leap-frog (n=5)	$P_s = -0.58p_p^5 + 0.721p_p^4 + 0.81p_p^3$	Medium
(g) Star-ring (n=5)	$P_s = [1-(1-3.6p_p^2+4.86p_p^3-2.884p_p^4+.656p_p^5)(1-0.5904p_p^5)]$	Good
(h) Star-ring-Star (n=5)	$P_s = [1-(1-3.6p_p^2+4.86p_p^3-2.884p_p^4+.656p_p^5)(1-0.5904p_p^5)][3.6p_p^2-4.86p_p^3+2.684p_p^4-0.656p_p^5]$	Medium
(i) Feedforward (n=4)	$P_s = .007p_p^4 + .081p_p^3 + 0.9p_p^2$	Medium
(j) Lattice (n=4)	$P_s = 0.6399\ p_p^4 - 3.29p_p^3 + 3.6p_p^2$	Good

MIMI 83 San Antoni

ISBN 0-88986

MINI AND MICROCOMPUTERS AND THEIR APPLICATIONS

A PUBLICATION OF
THE INTERNATIONAL SOCIETY FOR MINI AND MICROCOMPUTERS — ISMM

ACTA PRESS
ANAHEIM * CALGARY * ZURICH