Reliability of Basic Robot Automated Manufacturing Networks

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Abstract:

Reliability of robot networks is discussed and techniques given for its evaluation. Expressions are developed for the reliability of the most basic robot networks useful in automated manufacturing. These expressions are evaluated in the case of a fixed number, 6, of networked robots and used to obtain MTBF's for the practical comparison of the networks discussed. The results show a general preference toward the lattice structure.

I. Introduction

Due to the presence of microprocessors, robots are rapidly becoming the work-horses of automated manufacturing. Since manufacturing processes can involve many steps, and since individual robots are generally programmed to carry out but a few of these steps, it is clear that for complete automation a number of robots will be involved. To facilitate the final production it is also clear that these robots will need to communicate, and, hence, with their communication systems will form a robot network.

Toward an analysis of such systems we can represent a given robot network by several different graphs to incorporate different concepts of interest. Here we will use the overview graph in which each distinguished robot in the network is represented by a node and the communication links between nodal entities by a branch. In terms of this overview graph there are several configurations of primary interest, as is the case with electrical [1] and computer [2] networks.

Among the most basic of these graphs are the following [3]: a) star (for central purposes with master computer control), b) ring (for cyclic production lines), c) protected ring (for highly reliable cyclic production), d) linear (for open production lines), e) protected linear (the standard for highly reliable first-in-first-out production), f) double linear (for a complete spare back-up system) g) leap-frog (for ease of reconfiguring for multiple tasks), h) feed-forward (for open production lines with parallel constructions), i) lattice (for efficient and versitile multiple purpose production), j) star with ring (for good control in cyclic production).

The reliability of these robot networks will determine their overall cost effectiveness and in turn will, we believe, be a key factor in the specification of automated manufacturing plants. Following the notions developed in [4] we take the reliability of a robot network to be the probability that the network will perform a determined task within specified tolerance limits. This reliability may change with the task and, since a given robot network may be used for several tasks, there may be several reliabilities for the network, however, for this paper, both for simplicity and for ease of comparison, we assume a given robot network has a single reliability. Since the network is made up of communication links, represented by branches in the network graph, and robots, represented by nodes in the network graph, we calculate the network reliability assuming the reliability L for a primary communication link, C for back-up links (called here curve links and for which we generally assume C≤L), and N for the robot nodes (except N_1 is used for the master robot controller in the cases of star and star-ring networks).

In Table 1 we give the reliabilities for L ≠ C ≠ N ≠ N_1 while in Table 2 we reduce these under the assumptions that all robots have the same reliability and all links have the same reliability. For comparison purposes these are evaluated in Table 3 which also contains the Mean Times Between Failure (MTBF) for the various configurations. We use the combinatorial path enumeration technique [5] to evaluate the reliabilities of the mentioned robot networks.

II. Component Reliability

An understanding of how components, nodes, and links fail is essential to improving and evaluating the reliability of a network. Indeed it is through the reliability of the parts entering into a robot's construction that the reliability of a robot is determined, see for example [6, p.94] where reliability data on a Unimation robot is given. A component, a node, or a link can fail in either a catastrophic, or an intermittent mode. Electrical part failures are usually due to open or short circuits with the failure coming from a basic physical change that results in an identifiable failure mode. Early failures are often linked to design and manufacturing flaws or to a flaw in reliability testing itself.

Examples of early failures are wire bonds, poor connections, or bad protective coatings, as well as incorrect positioning of components. For electronic components the most destructive stresses are excessive voltage and temperature ranges, either steady-state or changing at rapid rates. Strong vibrations also contribute to stress related failures especially in industrial robots.

Failures of a component can usually be described for reliability purposes through the component's failure rate, the failure rate in this case being the inverse of the MTBF and denoted by λ, with the MBTF found by making a large number of tests to failure of the component. For a collection of components, such as a robot, the MTBF can be calculated as the average time to failure, the

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probability used in the averaging being the reliability $R(t)$. Thus

$$MTBF = \int_0^{\infty} R(t)dt \qquad (1)$$

When the reliability is exponential, as for an individual component, then $MTBF = 1/\lambda$. Other reliability related concepts of interest are the hazard rate, which is defined as the rate of change of the number of components that have failed at a particular time divided by the number of components surviving [7], and the useful life period, which is characterized by stress related failures.

To calculate failure probability for an entire robot network from component failure rates a stress analysis model can be built. Each component is examined and work sheets made up containing all factors that determine the failure for each node and link in the network. The reliabilities for each node and each link are combined to determine the reliability for the total robot network in the manner we carry out in the next section.

III. Network Reliability

Here we outline the methods used to obtain the Tables but for space reasons carrying out the calculations only for the lattice network, the calculations for others being similar. So that a fair comparison may be made we assume that all networks under discussion use six robots, that is, we assume there are six nodes in each graph.

Consider a path, to be now called an event E_n, from input to output; the reliability for production along this path will be the product of reliabilities of the nodes and links comprising this path. If there are n possible paths, $E_1, \ldots, E_n$, then the reliability R_s for the overall system will be given by

$$R_s = P(E_1 + E_2 + \ldots E_n) \qquad (2)$$

where P is reliability probability and + denotes union of the events.

We next evaluate the system reliability for the six node lattice network for which we will give two interpretations. In both cases we assume that the primary production process has inputs at node 1 and outputs at node 5. In the first case, though, we assume that links can only be traversed in the forward direction and that nodes 2 and 6 form alternate inputs and outputs in case the primary production line fails: in essence this interpretation is that of a backup production line in parallel with the primary one except that coupling exists between the two to allow for increased efficiency of use of equipment. In the second case inputs are limited to being at node 1 and outputs are always at node 5 with the other nodes being considered as being primarily available with backwards traversal of links being possible.

Under the first interpretation the six node lattice of Fig. 2 has the following four events

$$E_1 = N_1L_1N_3L_3N_5 \qquad (3a)$$
$$E_2 = N_1C_1N_4C_4N_5 \qquad (3b)$$
$$E_3 = N_2L_2N_4L_4N_6 \qquad (3c)$$
$$E_4 = N_2C_2N_3C_3N_6 \qquad (3d)$$

The system reliability expression is then

$$R_s = P(E_1+E_2+E_3+E_4)$$
$$= P(E_1) + P(E_2) + P(E_3) + P(E_4)$$
$$-P(E_1E_2)-P(E_1E_3)-P(E_1E_4)-P(E_2E_3)-P(E_2E_4)-P(E_3E_4)$$
$$+P(E_1E_2E_3)+P(E_1E_2E_4)+P(E_1E_3E_4)+P(E_2E_3E_4)$$
$$-P(E_1E_2E_3E_4) \qquad (4a)$$

In terms of N, L, and C this is

$$R_s = 2N^3(C^2+L^2) - [N^4(C^4+L^4)+2(N^5+N^6)(CL)^2]$$
$$+2N^6C^2L^2(C^2+L^2) - N^6C^4L^4 \qquad (4b)$$

If C=L this is

$$R_s = 4N^3L^2-2N^4L^4-2N^5L^4-2N^6L^4+4N^6L^6-N^6L^8 \qquad (4c)$$

For the MTBF this latter can be evaluated as a function of time using the failure rates λ_N and λ_L for the nodes and links, respectively.

$$R_s(t) = 4\exp[-(3\lambda_N+2\lambda_L)t] -2\exp[-(4\lambda_N+4\lambda_L)t]$$
$$-2\exp[-(5\lambda_N+4\lambda_L)t] -2\exp[-(6\lambda_N+4\lambda_L)t]$$
$$+4\exp[-(6\lambda_N+6\lambda_L)t] -\exp[-(6\lambda_N+8\lambda_L)t] \qquad (5a)$$

From equation (1) the MTBF is easily calculated

$$MTBF = [4/(3\lambda_N+2\lambda_L)] - [2/(4\lambda_N+4\lambda_L)]$$
$$-[2/(5\lambda_N+4\lambda_L)] - [2/(6\lambda_N+4\lambda_L)]$$
$$+[4/(6\lambda_N+6\lambda_L)] -[1/(6\lambda_N+8\lambda_L)] \qquad (5b)$$

For the Unimate 2000 robot which has a MTBF = 505 hours [6, p.84] we have $\lambda_N = 1970 \times 10^{-6}$/hours which after 26 hours gives N = 0.95 while from [8, p.32] we use L = 0.99 which when considered as $\exp(-\lambda_L t)$ evaluated at 26 hrs. yields $\lambda_L = 386 \times 10^{-6}$/hrs. and a MTBF of 2591 hrs. Using these in the above formula for the lattice MTBF we get 277 hours.

In the second interpretation of the lattice the procedure is the same for evaluating reliability and MTBF except that the events are different. In this case the previous E_1 & E_2 hold but E_3 & E_4 are not present. In place of E_3 & E_4 we have a number of other paths, as follows

$$E_3 = N_1C_1N_4L_2N_2C_2N_3L_3N_5 \qquad (6a)$$
$$E_4 = N_1L_1N_3C_3N_6L_4N_4C_4N_5 \qquad (6b)$$
$$E_5 = N_1C_1N_4L_4N_6C_3N_3L_3N_5 \qquad (6c)$$
$$E_6 = N_1L_1N_3C_2N_2L_2N_4C_4N_5 \qquad (6d)$$

There is also $E_7 = N_1C_1N_4L_2N_2C_2N_3C_3N_6L_4N_4C_4N_5$ which, however, we ignore since it has a return to N4 and, hence, path E_2 could have been used already. Calculations as before yield a MTBF = 194 hrs (the decrease being due to inputs restricted to robot one; if we allow node two as an input the MTBF appears to increase to about 290 hrs.). We also compare these results with using six robots in two disjoint linear production lines, one being a back-up for the other. For a linear production line of three equal nodes and two equal links we have $\lambda = 3\lambda_N+2\lambda_L$ which for the numbers used above gives $MTBF_1$ = 73 hrs.. By adding an identical back-up line we find, from $R(t) = 2\exp(-\lambda t)-\exp(-2\lambda t)$ since $R_s = P(E_1) + P(E_2) - P(E_1E_2) = 2N^3L^2-N^6L^4$, that $MTBF = (3/2)MTBF_1$ = 110 hrs.. From these calculations we can see that good improvement in system performance can result by going over to the lattice production line structure.

The Tables give the results for the various configurations of Fig. 1 where for the distinguished robots 1 we have used a failure rate equal to that of the links even though we believe it will be very hard to achieve in practice. We also note that the results do not improve in theory if return paths (that is paths which touch a given node more than once) are considered. However, there appear to be situations where there may be a possibility for improvement. Therefore, a theory to handle such situations is under development.

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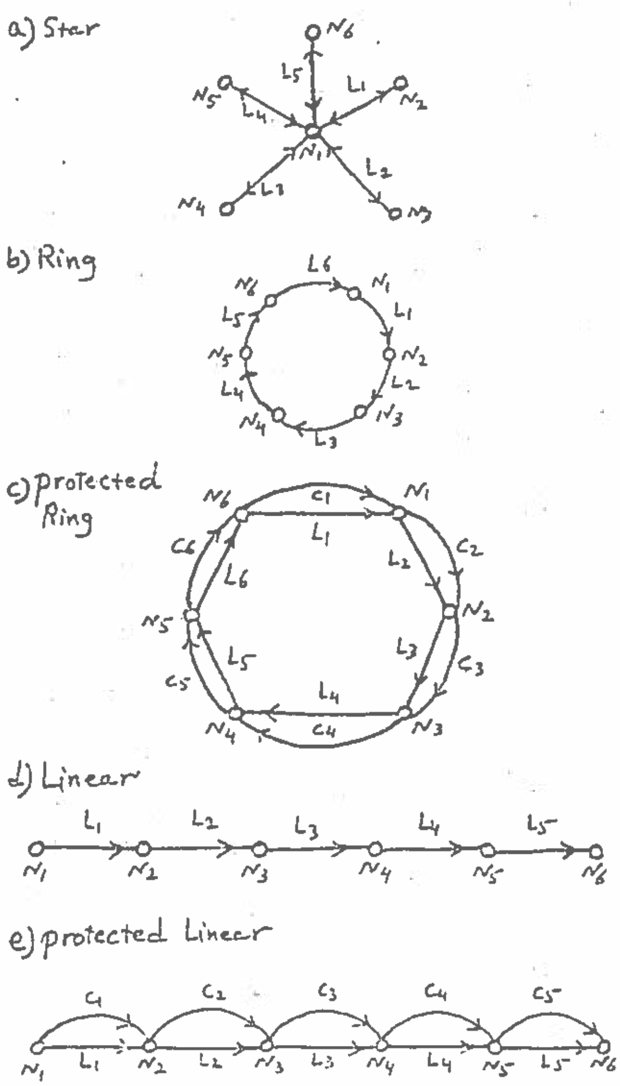
Figure 1. Basic Graphs of Robot Networks



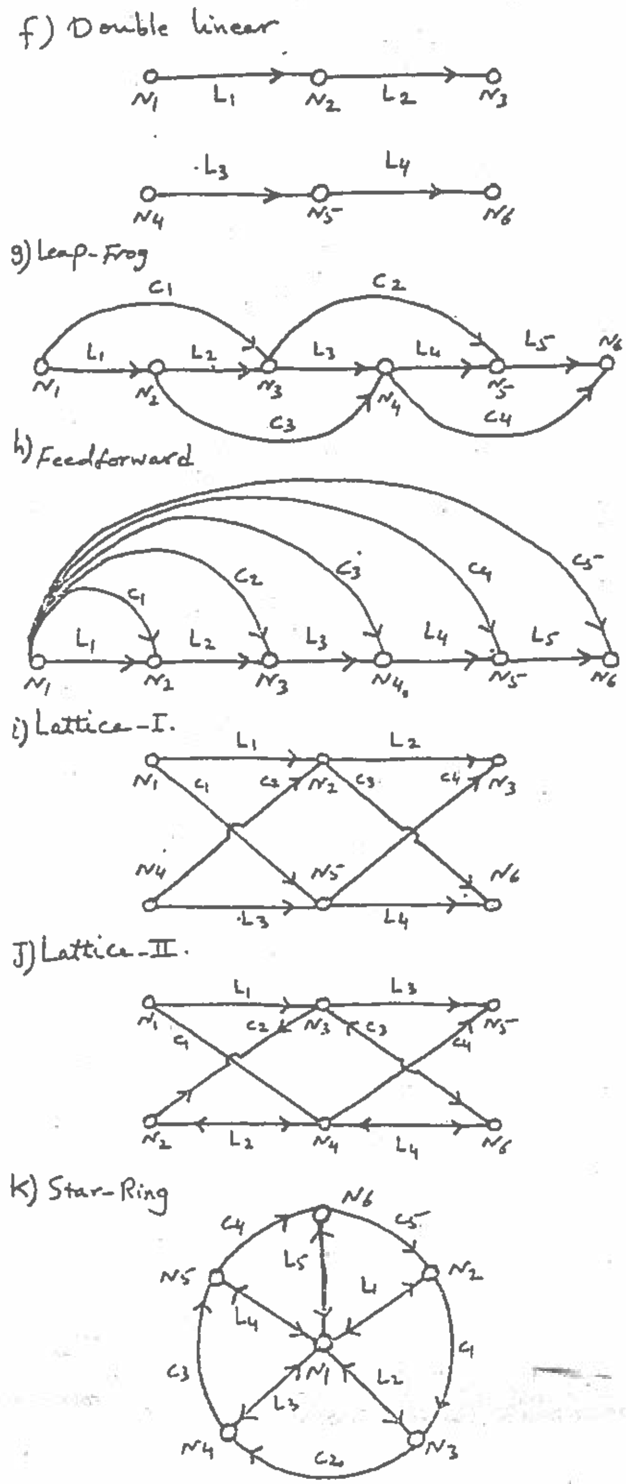


TABLE-I

Robot Network (n=6)		Reliability of Basic Robot Networks ($L \neq C \neq N \neq N_1$)
a)	Protected ring	$Rs = N^6L^6+N^6C^6+2N^6L^3C^3-2N^6L^3C^6-2N^6L^6C^3+N^6L^6C^6$
b)	Protected linear	$Rs = N^5C^5+N^6L^5+N^6L^2C^3-N^6L^2C^5+N^6L^3C^2-N^6L^3C^5-N^6L^5C^2-N^6L^5C^3+N^6L^5C^5$
c)	Leap-frog	$Rs = N^6L^5+2N^4LC^2+3N^5L^3C-3N^5L^3C^2-2N^6L^3C^3+2N^6L^3C^4-2N^6L^4C^2-2N^6L^4C^4 +3N^6L^5C+3N^6L^5C^2+2N^6L^5C^3$
d)	Feed-forward	$Rs = N^2C+N^3LC-N^3LC^2+N^4L^2C-2N^4L^2C^2+N^4L^2C^3+N^5L^3C-3N^5L^3C^2+3N^5L^3C^3-N^5L^3C^4 +N^6L^4C-3N^6L^4C^2+6N^6L^4C^3-4N^6L^4C^4+N^6L^5-6N^6L^5C+10N^6L^5C^2-10N^6L^5C^3 +6N^6L^5C^4-N^6L^5C^5$
e)	Lattice- 2	$Rs = N^3L^2+N^3C^2-N^4L^2C^2+4N^5L^2C^2-4N^5L^2C^3-4N^5L^3C^2+4N^5L^3C^3-2N^6L^3C^3+2N^6L^3C^4-2N^6L^4C^4$
f)	Star-ring	$Rs = N_1N^2L^2-N_1N^3L^3-N_1N^4L^4-N_1N^5L^5-2N_1N^5L^2C^5+N_1N^5L^3C^5+N_1^2N^3L^4+N_1^3N^4L^6 +N_1^4N^5L^8+N^5C^5.$

TABLE-II

Robot Network (n=6)		Reliability of Basic Robot Networks ($L=C \neq N \neq N_1$)
a)	Star	$Rs = N_1N^2L^2-N_1N^3L^3-N_1N^4L^4-N_1N^5L^5+N_1^2N^3L^4+N_1^3N^4L^6+N_1^4N^5L^8$
b)	Ring	$Rs = N^6L^6$
c)	Protected ring	$Rs = 4N^6L^6-4N^6L^9+N^6L^{12}$
d)	Linear	$Rs = N^6L^5$
e)	Protected Linear	$Rs = N^5L^5+3N^6L^5-2N^6L^7-2N^6L^8+N^6L^{10}$
f)	Double linear	$Rs = 2N^3L^2-N^6L^4$
g)	Leap-frog	$Rs \quad 2N^4L^3+3N^5L^4-3N^5L^5-7N^6L^6+5N^6L^7+N^6L^5$
h)	Feedforward	$Rs = N^2L+N^3L^2-N^3L^3+N^4L^3+N^4L^3-2N^4L^4+N^5L^4-3N^5L^5+3N^5L^6-N^5L^7+2N^6L^5-9N^6L^6 +16N^6L^7-14N^6L^8+6N^6L^9-N^6L^{10}$
i)	Lattice- 1	$Rs = 4N^3L^2-2N^4L^4-2N^5L^4-2N^6L^4+4N^6L^6-N^6L^3$
j)	Lattice- 2	$Rs = 2N^3L^2-N^4L^4+4N^5L^4-8N^5L^5+4N^5L^6-2N^6L^6+4N^6L^7-2N^6L^8$
k)	Star-ring	$Rs = N_1N^2L^2-N_1N^3L^3-N_1N^4L^4-N_1N^5L^5-2N_1N^5L^7+N_1N^5L^8+N_1^2N^3L^4+N_1^3N^4L^6+N_1^4N^5L^8+N^5L^5$

TABLE-III

Robot Network (n=6)		Reliability (26hrs) $L=C \neq N \neq N_1$	Reliability (26hrs) $L \neq C \neq N \neq N_1$	MTBF (hrs)	Vulnerability (Survivability)
a)	Star	0.7868		157	good
b)	Ring	0.6919		70.7	fair
c)	Protected ring	0.7335	0.72317	91.9	good
d)	Linear	0.6982		72.7	fair
e)	Protected linear	0.7681	0.7489	94.8	good
f)	Double linear	0.97471		110	very high
g)	Leap-frog	0.883188	0.8637897	151.9	high
h)	Feed-forward	0.9025	0.8727	241.1	very high
i)	Lattice-1	0.9891		277.2	super
j)	Lattice-2	0.9025	0.8894	193.9	very high
k)	Star-ring	0.800[illegible]	0.795[illegible]	162.5	high

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