Distributed Intelligent Control of Unreliable Manufacturing Systems

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Abstract: - We consider assembly-disassembly single-part type production networks, with finite buffers and unreliable machines that can operate at various processing rates. Three intelligent control modules, namely, *line*, *assembly*, and *disassembly* controller, are developed. The overall control objective is twofold. First, is to keep the work-in-process and cycle time as low as possible, and secondly, to maintain high machine utilization and throughput. These are achieved by adjusting the production rate in each production stage so that workflow is balanced and the extreme events of idle periods (machine starving or blocking), are reduced. After a series of simulation runs, it has been observed that the proposed approach is superior to a conventional control policy for a variety of performance metrics.

Key-Words: - Production networks, work-in-process, intelligent control, fuzzy logic *CSCC'99* Proc.pp..3911-3915

1 Introduction

Many changes have taken place in manufacturing, leading to many advances in manufacturing management during the last three decades. These advances usually built on earlier concepts, utilizing their strengths while introducing new ideas to meet unsolved challenges. Concepts such as, throughput, cycle time, work-in-process, flexibility, quality, equipment utilization etc., are traditionally some of the most important performance measures of manufacturing systems. The increased need for speedy and punctual delivery has placed more emphasis on the reduction of product cycle time and the inventory-related costs. It seems that scheduling or control policies that keep the Work-In-Process (WIP) in low levels, are important because of various reasons [5], [7]:

- Capital invested to inventories as long as they remain in the factory or the warehouse provides no profit.
- High in-process inventories increase cycle times and decreases responsiveness to customers.
- High in-process inventories require more space and expensive material handling equipment increasing the invested capital.
- Inventory quality decreases as the unfinished items remain to the factory because the longer the items remain in the factory the more they are vulnerable to damage.

Many researchers have studied the problem of WIP management in unreliable production networks [1], [2], [3], [9], [10]. It is common belief, however, that the problem of scheduling production systems in order to minimize costs due to inventories and non-satisfaction of demand, cannot be solved analytically for complex systems. Since neither analytical nor computational solutions are attainable, heuristic policies are suggested to control job flow within production systems ([2], [3]).

Here we suggest a distributed fuzzy control methodology for single-part-type production networks. The overall control objective is to keep the work-in-process and cycle time as low as possible, and at the same time to maintain high machine utilization and throughput. In contrast to traditional produce-at-capacity approach according to which the system always operates at its maximum capacity, we control the production rate in each production stage in a way that eliminates extreme events of idle periods, due to machine starving or blocking.

The next section describes the architecture of the three production modules of the distributed fuzzy logic control system that is proposed. There it is also presented the mathematical formulation of the fuzzy production control problem. In section 3, simulation results are drawn along with comparisons of the produce-at-capacity and the proposed approach. Finally, in Section 4, the contribution of this work is summarized and further research is outlined.

2 The Production Control Modules

A production system is usually viewed as a network of machines/workstations and buffers.

Items receive an operation at each machine and wait for the next operation in a buffer with finite capacity. Random machine breakdowns disturb the production process and phenomena such as starvation or/and blocking, may occur. Because of a failed machine with operational neighbors, the level of the downstream buffer decreases, while the level of the upstream buffer increases. If the repair time is big enough, the broken machine will either block the next station or starve the previous one. This adverse effect will propagate throughout the system.

The events that can happen in production network are changes in buffer states and changes in machine states. The buffers can be full or empty and the machines can be up (operating) or down (under repair). When a machine is up can be starved if one of the preceding buffers is empty. In this case the machine is forced to produce in the rate of the machine feeding the empty buffer. Respectively, if a machine is up can be blocked if one of the succeeding buffers is full. Then the machine rate becomes equal to the rate of the machine succeeding the full buffer. When a machine breaks down the preceding machines remain operating until one of their downstream buffer is filled. Similarly, the succeeding machines continue processing until their upstream buffers become empty.

In this study, we introduce three modules for production line (Fig.1a), assembly (Fig.1b) and disassembly (Fig.1c) networks control. The line module includes a machine $M_{i,}$ which takes unfinished items from an upstream buffer $B_{j,i}$ and after processing sends them to a downstream buffer $B_{i,l}$. In the assembly operation a machine M_i obtains two or more parts or subassemblies, following an assembly factor $d_{j,i}$, from more than one upstream buffers $B_{j,i}$, brings them together to form a single unit and send it to a downstream buffer $B_{i,l}$ as shown

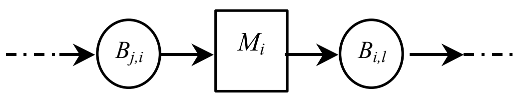

Fig.1a: The line module

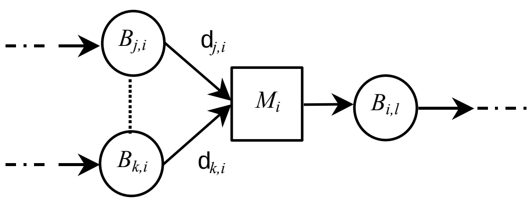

Fig.1b: The assembly module

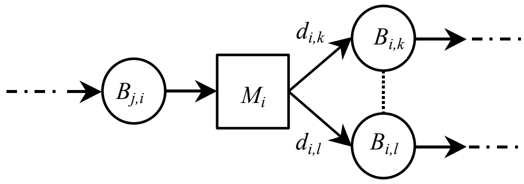

Fig.1c: The disassembly module

in Fig.1b. The disassembly operation involves a machine M_i taking unfinished single units from one upstream buffer $B_{j,i}$, separates them to two or more parts or subassemblies, following a disassembly factor $d_{i,j}$, and sends them to downstream buffers $B_{i,k}$ as shown in Fig.1c. These modules, if connected to each other, can represent manufacturing networks of various layouts.

Each of the three modules can be seen as a fuzzy controller (Fig.2). The input variables of each controller are:

- the buffers levels b_{ij} and b_{ik} of the upstream and downstream buffers,
- the state ms_i of machine M_i.

The output variable of every controller is the processing rate r_i of each machine M_i. The buffer levels and the processing rate of each machine take linguistic variations with certain membership functions. The machine state ms_i is crisp and can be 1 (up) or 0 (down).

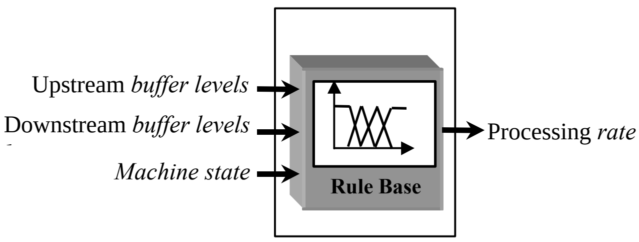

Fig.2: Inputs and output of the control module.

The control policy tends to keep buffer levels in a normal position, so that events of starvation or blocking are prevented. A buffer tends to be empty when the upstream machine is either under repair or producing in a slower rate than the downstream machine. Similarly a buffer tends to fill when the downstream machine is either under repair or producing in a slower rate than the upstream machine. The controllers keep buffers neither full nor empty regulating the machine rates. When a buffer tends to be full the controller is increasing the rate of the downstream machine and decreasing the rate of the upstream machine. In the same way when a buffer tend to be empty the controller is increasing the rate of the upstream machine and decreasing the rate of the downstream machine. The information needed to synchronize the operation of the production network is transferred to each control module by the level change of each buffer. Every event occurring in the production network is affecting the levels of buffers close to the area of the event. In that way the production system is operating in satisfactory rates while the WIP is kept in low levels.

The rule base of the *line control module* contains 15 rules of the following form

IF $b_{j,i}$ is $LB^{(k)}$ AND $b_{i,l}$ is $LB^{(k)}$ AND ms_i is $LMS_i^{(k)}$ THEN r_i is $LR_i^{(k)}$, (1)

where, k is the rule number (k=1,…,15), i is the number of machine or workstation, LB is a linguistic value of the variable *buffer level b* with term set B ={*Empty*, *Almost Empty*, *OK*, *Almost Full*, *Full*}, ms_i denotes the state of machine i, which can be either 1 (operative) or 0 (stopped) and consequently MS = {*zero*, *one*}. The *production rate r* takes linguistic values LR from the term set R = {*Zero*, *Low*, *Normal*, *High*}. The mathematical meaning of the k-th rule, for $LMS_i^{(k)}$ = *one*, can be given as a fuzzy relation $FR^{(k)}$ on $B\times R$, which in the membership function domain is

$$\mu_{FR^{(k)}}(b_{j,i}, b_{i,l}, r_i) = f_{\rightarrow}\left[\mu_{LB^{(k)}}(b_{j,i}), \mu_{LB^{(k)}}(b_{i,l}), \mu_{LR^{(k)}}(r_i)\right], \quad (2)$$

where, $f_{\rightarrow}$= min for rules of the Mamdani type. Obviously, whenever $LMS_i^{(k)}$ = *zero* the production rate r takes the *Zero* value from the R term set.

Let us now assume that the machine is not stopped, and the actual buffer levels of the upstream and downstream buffers can be represented as $b^*_{j,i}$ and $b^*_{i,l}$ with membership functions $\mu^*_B(b_{j,i})$ and $\mu^*_B(b_{i,l})$, respectively. The membership function of the conjunction of the two inputs, for AND = min, is

$$\mu^*_{AND}(b_{j,i}, b_{i,l}) = \mu^*_B(b_{j,i}) \wedge \mu^*_B(b_{i,l}), \quad (3)$$

The production rate r_i^*, e.g. the control action at every time instant is given by

$$r_i^* = \frac{\sum r_i \mu^*_R(r_i)}{\sum \mu^*_R(r_i)}, \quad (4)$$

where $\mu^*_R(r_i)$ is the membership function of the aggregated production rate, which is computed by applying the max-min composition on the outcome of (2) and (3). That is

$$\mu^*_R(r_i) = \max_{b_i, b_{i+1}} \min\left[\mu^*_{AND}(b_{j,i}, b_{i,l}), \mu_{FR^{(k)}}(b_{j,i}, b_{i,l}, r_i)\right] \quad (5)$$

Similarly, the generic rule of the *assembly* and *disassembly control modules* can be written as follows:

IF $b_{j,i}$ is $LB^{(k)}$ AND … AND $b_{i,l}$ is $LB^{(k)}$ AND ms_i is $LMS_i^{(k)}$ THEN r_i is $LR_i^{(k)}$, (6)

3 Simulation Testing and Results

In this section, we test the proposed control approach and the well known produce-at-capacity policy, according to which the machines produce in their maximum rate when they are operational (up, not blocked, not starved) or zero in any other case. We assume that the flow of parts within the system is continuous. In the continuous-flow simulation the discrete production is approximated by the production of a liquid product [8]. The assumptions we made for the simulation of the production networks under study, are as follows:

1. Machines fail randomly with a probability p_i, which is given by

   $$p_i = \frac{r_i}{c_0} \quad i = 1,\ldots,N. \quad (7)$$

   where r_i is the processing rate of machine M_i and c_0 is constant.
2. Machines are repaired randomly with probability pr_i.
3. Time to failure and time to repair are geometrically distributed.
4. All machines operate at known, but not necessarily equal, rates. Each machine produces in a rate $r_i \le \mu_i$, where μ_i is the maximum processing rate of machine M_i.
5. The initial buffers B_I are infinite sources of raw material and consequently the initial machines are never starved.
6. The last buffer B_O has infinite storage capacity, so the last machine is never blocked.
7. Buffers between adjacent machines M_i, M_j have finite capacities BC_{ij}, i, j = 1,…, N
8. Set up times or transportation times are negligible or are included in the processing time.

For the network of Figure 3, two continuous-flow simulation algorithms were implemented, one for each tested policy. *Matlab s Fuzzy Logic Toolbox* and *Simulink* were the software tools for building and testing the two approaches.

The production network of Fig.3 consists of two line, two assembly and one disassembly modules.

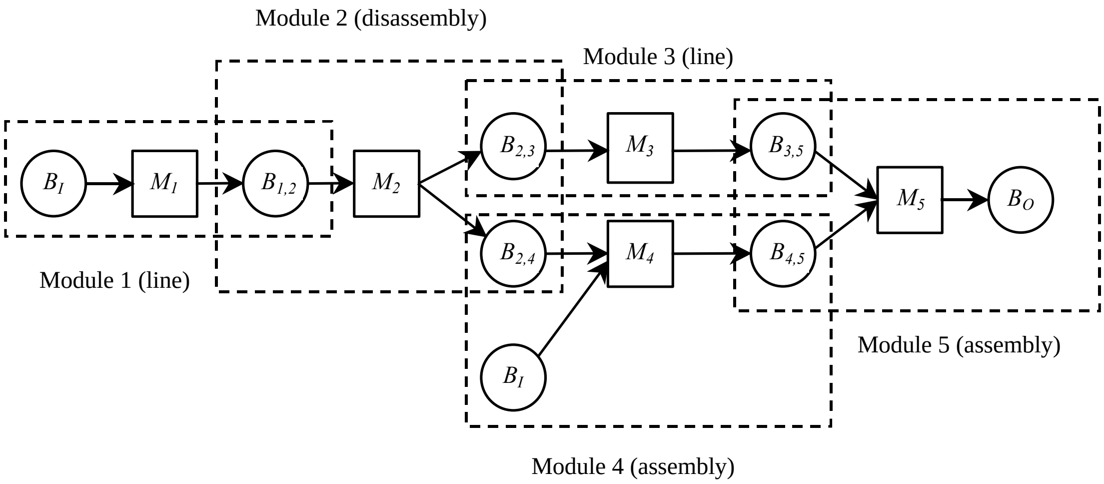

Fig.3: The testing network

Note that the control modules are connected to each other through common buffers. All machines have the same maximum production rate, which is m_i=20 parts per time unit. All buffer capacities are equal to BC_{ij}=50 parts, apart from the infinite initial buffers (B_I) and the last infinite buffer (B_O). The failure probability of all machines is given by

$$p_i = \frac{r_i}{100}, \tag{8}$$

The machine repair probability is $pr_i=0.4$. The assembly and disassembly factors are equal to one, $d_{j,i} = d_{i,j}$ =1. The buffer levels at any time instant, is given by the following equation:

$$b_{j,i}(t_{k+1}) = b_{j,i}(t_k) + [r_j(t_k) - r_i(t_k)](t_{k+1} - t_k), \tag{9}$$

where t_k ,t_{k+1} are the times when control actions (changes in processing rates), happen. The production of a machine M_i is

$$PR_i(t_{k+1}) = PR_i(t_k) + r_i(t_k)(t_{k+1} - t_k), \tag{10}$$

The mean processing rate mr_i is given by

$$mr_i = \frac{PR_i(T)}{T}, \tag{11}$$

where T is the total simulation time. Comparative results for the total WIP, cycle time and throughput, are shown in Fig.4a-d.

It is clear from the above diagrams that the proposed distributed intelligent control system reduces substantially the WIP and cycle time of the network while the throughput reduction is not noticeable.

4 Conclusions

We have presented a new distributed fuzzy controller, which efficiently balances the buffer levels by regulating the processing rate of each machine. The proposed control system consists of three independent modules and can be applied to production networks of general topology. A continuous-flow simulator is used to compare the fuzzy with the produce-at-capacity policy. It turns out that the fuzzy policy provides lower WIP, higher system utilization, smaller product cycle time, while the throughput is less than 10% lower.

Acknowledgments

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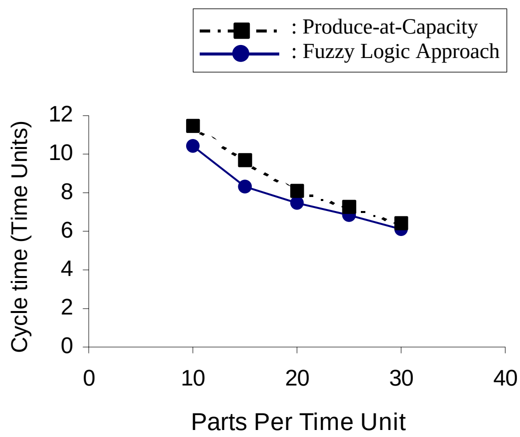

Fig.4a: Cycle Time Versus Processing Rates

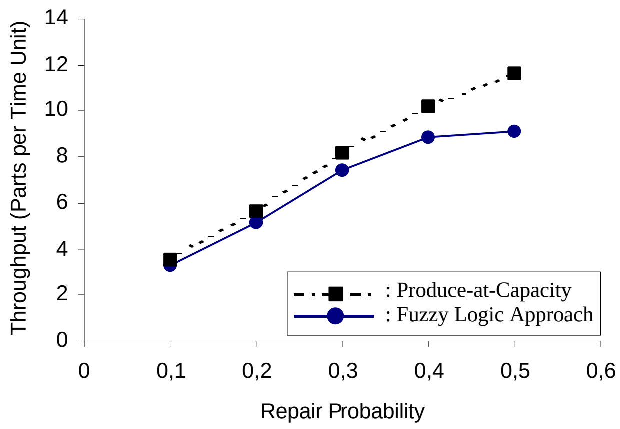

Fig.4b: Throughput Versus Repair Probability

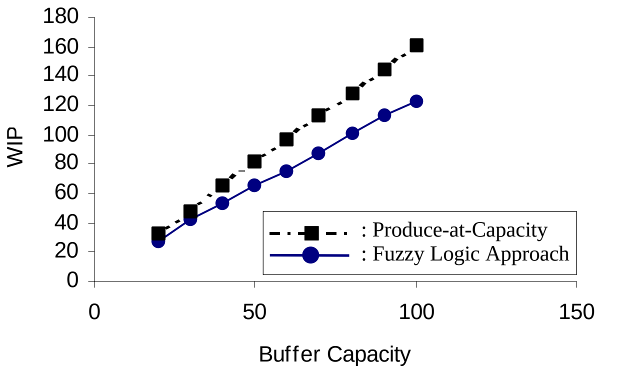

Fig.4c: Total WIP Versus Buffer Capacity

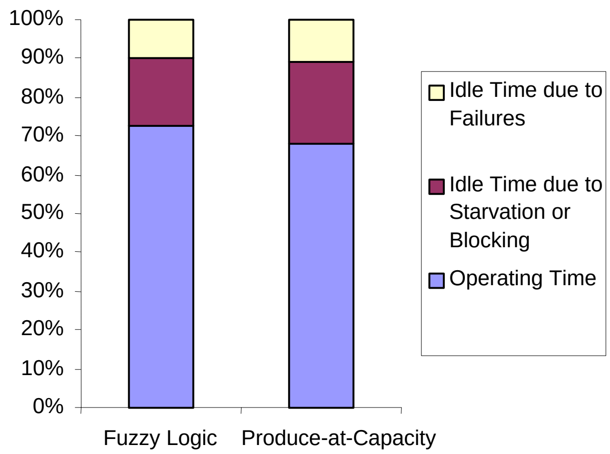

Fig.4d: System Utilization

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