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The deadlock protection method used in the production systems

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Abstract: The subject matter of that paper is the deadlock protection method. The proposed method enables to the sequential ordering of the processes realisation to prevent the system from the occurrence of the cycle of mutual expectations being one of the conditions necessary for the deadlock occurrence. The deadlock may take place only in the systems with the closed structure at the resources belonging to the basic cycle. The basic cycles are found using the procedures adopted from Graph Theory.

Keywords: Distributed control system; Deadlock; Graph contour; Contour search algorithm

1. INTRODUCTION

Contemporary enterprises more and more often produce a wide range of products because of high customer requirements and in turn production frequently is realised in small production batches with short system cycles. The requirements needed for that production realisation meet flexible production systems being characterised by distributed control of production flow. Distributed control is characteristic of the biological, holonic and cellular manufacturing systems as well as of the systems in which local dispatching rules are allocated at the production resources. The R_i local dispatching rule determines the number and the sequence of the processes executed at the *i*th resource. Moreover, each realisation of the R_i local dispatching rule guarantees at least one execution of the operation belonging to each process, whose production route crosses the shared resource. After the realisation of the last operation from the given dispatching rule comeback to the first operation from that rule takes place. The proposed rule construction, which takes into consideration the synchronising role of the system bottlenecks, guarantees the cyclic behaviour of the production system work. Production planning and control in production systems based on the local dispatching rule is the subject matter of the considerations in the next part of that paper.

2. PROBLEM FORMULATION

Given is the production system working for needs of small- and medium-batch multi-assortment concurrent and rhythmic production. For the considered systems belonging to the group of the distributed control systems the deadlock-free system behaviour should be ensured. A deadlock in the concurrent production system takes place when the following necessary conditions concurrently occur: the exclusive-like mode, non-expropriate of the process, shared resources, the cycle of mutual expectations. There are three main strategies ensuring the deadlock-free system behaviour as follows [2]: deadlock protection, deadlock avoiding, deadlock finding and eliminating. The producer should choose one of the proposed strategies in order to ensure the deadlock-free system behaviour. For the distributed control systems only the strategy of deadlock protection is useful. That strategy boils down to imposing the restrictions which cause non-fulfilment of one of the conditions necessary for the deadlock occurrence. That task can be solved using the deadlock protection method. According to the proposed method the deadlock protection consists in the sequential ordering of the processes realisation to prevent the system from the occurrence of the cycle of mutual expectations. The sequence of the processes realisation is specified using the local dispatching rule. Primarily, it is necessary to determine the resources at which may take place the deadlock stopping the production flow in the system.

3. THE TOPOLOGY OF PRODUCTION SYSTEMS

The work of the production system is to a large extent determined by its topology. There are three basic kinds of the production system structures: linear, open and closed ones [3]. The most important for the presented considerations is the closed system structure. The system with the closed structure is characterised by the existence of at least one closed cycle. A closed cycle is defined as a set of production routes crossing limited number of resources in such a way that starting from any resource and moving along production routes or their parts, in any direction of their flows, it is possible to return to the resource we started from, not crossing the same route more than once. In the systems with the linear and open structure the cycle of mutual expectations cannot occur. Thus, one of the conditions necessary for the deadlock occurrence is not fulfilled. However, in the systems with the closed structure the cycle of mutual expectations can occur and the deadlock can appear.

4. THE SYSTEM DEADLOCK AND THE CLOSED CYCLE

The cycle of mutual expectations is one of the conditions necessary for the deadlock occurrence. The avoiding of the appearing of that cycle through the allocation of the local dispatching rules at the resources is equivalent to ensuring deadlock-free system behaviour. The cycle of mutual expectations can take place only at the shared resources belonging to the closed cycles. Thus, at first the closed cycles should be identified. A special kind of a closed cycle in which the cycle of mutual expectations can arise is a basic cycle. A basic cycle is defined as a set of production routes crossing a limited number of resources in such a way that starting from any resource and moving along production routes or their parts, in accordance with the direction of their flows, it is possible to return to the resource we started from, not crossing the same route more than once. In the considered system characterised by the closed structure the deadlock arises when for each pair of the $(M_i, M_k)_j$ neighbouring resources belonging to the basic cycle the following conditions concurrently occur [4]: according to the rule construction the Pj process is admitted to realisation at the Mk resource, according to the production route the previous operation of the Pj process has been realised at the Mi resource, the inter-resources buffer allocated between Mi and Mk is empty. In order to formulate the sufficient conditions guaranteeing deadlock-free system behaviour the algorithm of the basic cycle identification has been worked out.

5. THE CONTOUR SEARCH ALGORITHM

The contour search algorithm and the procedures controlling production flow in the systems including the basic cycles have been formulated within the confines of the deadlock protection method. For the identification of the basic cycles occurring in the production system the contour search algorithm adopted from Graph Theory is used [5]. It is possible because a graph is a model that enables description of a production system structure. The G digraph is defined as the $<N,A>$ ordered pair, where N: the set of the vertices; A: the set of the (x,y) ordered pair corresponding with the graph edges; x, y: the elements of the N set of the vertices. The contour of the G digraph, is the $x_1, x_2, ... ,x_k, x_1$ sequence for which the (x_i, x_{i+1}) pair belongs to the A set for $(i = 1,2,...,k-1)$ and the (x_k, x_1) pair also belongs to the A set. The elementary contour is a contour for which the $x_i \neq x_j$ inequality takes place for each $i \neq j$ [6]. For the description of the production system structure Graph Theory has been used. It has been assumed that the M_i production resources are represented by the G graph vertices described by the figures of the M_i adequate production resources, $i=1, 2, \ldots, m$. Moreover, the parts of the production routes allocated between each pair of the neighbouring resources are represented by the (x,y) ordered pair corresponding with the graph edges. Note that the direction of the production flow has been taken into consideration. The elementary contour according to Graph Theory is adequate to the basic cycle in the production system structure. Thus, the identification of the basic cycle occurring in the production system structure requires the identification of the elementary contour in the graph [7]. The identification of the graph contours primarily requires the topological numeration of the graph vertices. The topological numeration of the G graph vertices consists in the assignation a natural number to each graph vertex. It has been assumed that given are the x graph vertex and the y graph vertex connected by the (x,y) graph edges. If the condition $tnr(x) < tnr(y)$ is fulfilled then the $tnr(x)$ natural number is called the topological number of the x graph vertex, where $tnr(x)$: the natural number assigned to the x graph vertex, $x \in (1, 2, ... ,m)$; $tnr(y)$: the natural number assigned to the y graph vertex, $y \in (1, 2, ... ,m)$, $x \neq y$.

The deadlock protection method requires the action consistent with the consecutive steps of the contour graph algorithm. The steps of the contour graph algorithm are as follows [8]:

1. The construction of the T vertices list. At the beginning all graph vertices for which the predecessors' number is equal zero on the T vertices list are allocated.
2. The consideration of the consecutive vertices from the T vertices list until the list end.
3. The allocation of the x next vertex being in order on the T vertices list. The elimination of all (x,y) edges exiting the x vertex. When the predecessors' number of the y vertex after that elimination equals zero, then the y vertex is joined to the T list end.
4. If the allocation of all graph vertices on the T list is possible according to the steps from 1 to 3, then the considered graph does not include any contours. The vertices order on the T list is adequate to their topological numeration. The algorithm is ended.
5. If the allocation of all graph vertices on the T list is not possible according to the steps from 1 to 3 then the considered graph includes at least one contour. The graph does not include any contours only if the topological numeration of its vertices exists. Thus, the vertices from the T list are not crossed by the searched contours. The graph contours should be searched in the N-T set, where N: the set of all vertices; T: the set of the vertices allocate on the T list.
6. The search of the graph contours with the aid of the depth-first search (DFS) algorithm with backtracking. According to the DFS algorithm one starts from the x specific vertex

and moves along the route generated by the *S(x)* successors list. The successors of checked vertex create the tree of next successors. The consecutive vertices are checked until there are not any non-checked successors. Then one backtracks to the vertex which has some non-checked successors. When all routes starting from the *x* vertex are verified it is necessary to choose another vertex and repeat all procedures. It has been assumed that each graph vertex is connected with one checked or non-checked attribute. It means that the recurrent procedure of the graph contours search is considered. If the last from the generated vertices sequence is at the same time the first one that sequence, then the elementary contour has been found.

The deadlock protection method enables to check, whether the contours in the given graph exist and find the sets of the graph vertices forming the contours and in turn determine all elementary contours. The determined elementary contours are adequate to the basic cycles existing in the production system structure. The determination of the basic cycles belongs to combinatorial tasks. In the most of cases the application of the depth-first search (DFS) algorithm with backtracking adopted from Graph Theory needs a lot shorter time comparing with full calculations [8].

6. CONCLUSIONS

For the distributed control systems working for needs of multi-assortment concurrent and rhythmic production the deadlock-free system behaviour should be ensured. One of possible ways to that task realisation is the deadlock protection strategy. The deadlock protection method consists in the sequential ordering of the processes realisation to prevent the system from the occurrence of the cycle of mutual expectations. According to that method the production system structure is transformed into the digraph. The elementary contour according to Graph Theory is adequate to the basic cycle in the production system structure. Thus, the identification of the elementary contour in the graph is equivalent to the identification of the basic cycle occurring in the production system and in turn the system deadlocks. The allocation of the right local dispatching rules at the resources belonging to the found basic cycles protects the production system from the deadlock occurrence.

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