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Implementation of reliable net-centric management of IoT industrial workshop for small-scale production

Igor Chernorutsky ¹, Vsevolod Kotlyarov ¹, Rudrapatna Shyamasundar ², Alexey Tolstoles ¹ and Nikita Voinov ^{1*}

¹ Peter the Great Saint Petersburg Polytechnic University, Polytechnicheskaya st., 29, Saint Petersburg, 195251, Russia

² Indian Institute of Technology Bombay, Main Gate Rd, IIT Area, Powai, Mumbai, 400076, India

* E-mail: voinov@ics2.ecd.spbstu.ru

Abstract. There are various approaches to the formalization of systems that operate in accordance with the principles of the Internet of Things (IoT). The main goal of creating such formalisms is the need to build complete digital models of real objects used for the purposes of their optimal management and the rational (optimal) use of available resources. The methods based on network models of processes, which develop in time are among the most effective approaches to digital modelling. However, the existing network technologies can be effectively used in the analysis of essentially single-level processes only and can hardly be used to model nested hierarchical systems due to insufficient formalization thereof. The proposed work is intended to fill the specified gap to some extent.

Another issue in the field of management of the industrial IoT workshop is ensuring the reliability of the production process, which should be checked via modelling and simulation of the process. The work is aimed at automation of the small-scaled production site. Digital simulation is used as the research method. The multilevel representation of a workshop infrastructure based on IoT technology is described. An abstract network set-theoretic model of multistage processes developing in time is constructed and substantiated in this paper. The constructed model allows you to automatically perform an unlimited number of nested processes within a given hierarchical structure and implement some algorithmic methods thereby for decomposition of the complex systems. Furthermore, the method of reliable solution of scheduling and managing automation of multicriteria control network is described, which provides a balance between a set of target efficiency criteria of technological processes at different stages.

The issues of application of the developed concept of network modelling to improve the performance of production sites of various kinds are considered. It is assumed that the main task of the production site is manufacturing a different range of parts from workpieces. In addition, each workpiece must go through certain stages of processing. These operations are interdependent, and the technological process itself is characterized by transitions from the initial state to the final state within the framework of a certain state graph. The developed model allows calculating the optimal path for this graph based on the principles of dynamic programming. The latter leads to savings of both temporary and other resources taken into account in the model.

1. Introduction



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Today the driving trend of the manufacturing of the future is Industry 4.0. Its core principle consists in organizing the workshop automation basing on the intranet networks control which integrates information exchange among computer numerical control (CNC) machines, robots and other terminal equipment with means of smart operational and strategic control of technological processes through control nodes forming the so-called Industrial Internet of Things (IIoT).

One of the most demanded features of such automation systems is the ability thereof to adapt to various technological processes of the small-scale or single-part manufacturing in the fields of machine building, processing of raw materials, assembly of multicomponent products and so on [1]. The automation of small-scale net-centric manufacturing in machinery requires solution of many tasks such as automated formalization of technological processes (conversion of existing and new operative documentation into technological paths of commands), distribution of workshop equipment, materials and tools between technological paths, monitoring of concurrent processes of supply and execution, analysis, network planning and manufacturing optimization considering miscellaneous criteria distributed among three levels of industrial network. Reliability is achieved by applying proving methods in the processes of design for identifying all behavioral scenarios of manufacturing workshop and monitoring of automated technological processes.

2. Features of the workshop with network-centric control

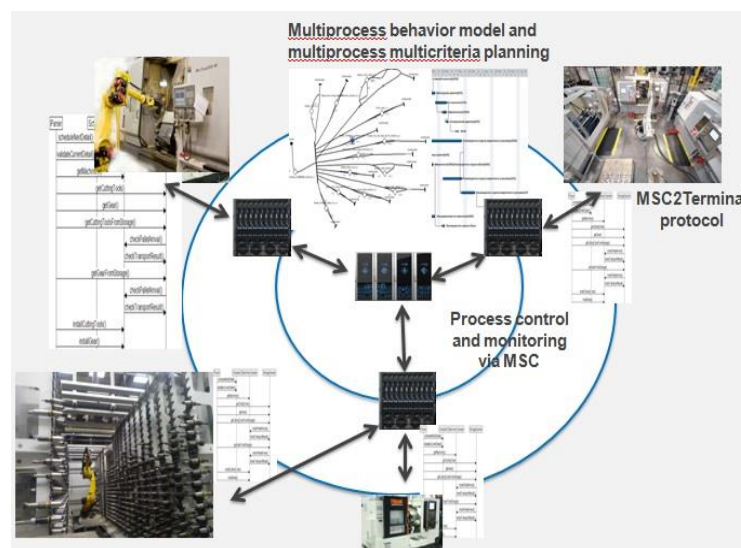


Figure 1. Machinery workshop with three levels of network-centric control

The example of the machinery workshop with three levels of network-centric control is given in figure 1. The levels depicted are as follows:

1. The first level works as a basis for controlling the technological macro-operations of machines, robots and other terminal equipment;
2. The second level carries out technological processes (control of the execution of sequences of technological macro-operations);
3. The third level manages multi-criteria hierarchical optimization and manufacturing planning of the technological processes (TP).

The modern CNC machines are smart enough to automatically carry out the complex action sequences, if they have the required materials, tools and equipment. Therefore, we can afford not to go into details of single action performed by the machine and instead operate with sequences of single actions which form the so-called macro-operations, for example, of making a workpiece surface. Each macro-operation has a set of parameters defining its modes, constraints and conditions.

The macro-operations are transmitted between objects at the first and second control levels. The technologies of making various details are described in terms of optimized sequences of macro-operations, which satisfy the multi-criteria hierarchical optimization from the third control level.

The network-centric workshop reliability is ensured in several following ways:

- Technological scenarios

Each scenario is represented by a tree of macrooperations, in which there is a path - a sequence of branches describing the technology of manufacturing a part in the absence of any events and conditions that violate the pre-defined conditions and restrictions on the operation. The tree nodes for each macro-operation contain alternative ways to work out all situations related to the violation of the conditions of use of the operation, providing the appropriate response. As a result, the completeness of reactions is provided in the tree at each node with alternatives.

The distribution of concurrent work, provided by the technology of manufacturing various details, on the resources of the workshop, is carried out in the planning process.

- Transport protocols

The reliability is achieved by monitoring the history of interactions in the technological processes, detection and processing of incorrect incidents.

We use the Readers-Writers Flow Model (RWFM) created by N.V.Narendra Kumar and R.K.Shyamasundar [2] to dynamically label the transactions of the IoT, and derive the constraints to be satisfied by the various components and the interactions thereof to preserve the desired security and privacy requirements.

RWFM is obtained by recasting the Denning's label model, and has a label structure that: explicitly captures the readers and writers of information, makes the semantics of labels explicit, and immediately provides an intuition for its position in the lattice flow policy [3, 4]. As a result of the monitoring of the behaviour history of signal transmission at the transport level, it is possible to identify situations of incorrect behaviour and to prevent it.

- Continuous monitoring of the system states

The monitoring of the state of network-centric production facilities ensures prompt tracking of discrepancies with the work distribution plan for machines, robots, warehouses, and support personnel, which allows you to quickly reschedule on the fly and make appropriate corrections to the production process.

3. Procedure for automating creation of a reliable behavioral model of the iiot system in the process of symbolic verification

The reliability of network-centric manufacturing in this approach is provided through systematic application of the following procedure in the process of creating software for IIoT technological applications:

1. Creation of a multilevel formal model of technological scenarios for the machinery workshop production on the basis of an event-oriented approach.
2. Proof of the correctness of the formal model and fixation of the acceptable ranges of parameters and attributes of scenarios corresponding to the correct behaviour thereof [5].
3. Proof of completeness of behavioral technological scenarios in the process of symbolic verification [5].
4. Generation of a set of behavioral scenarios covering all the requirements for the technology description basing on a detailed formal model [6].
5. Generation of a set of control tests for a set of specified scenarios and provision of testing of the technological process with a mapping of the causes and consequences of errors on the original model [7].
6. Analysis of the behavior of all operational modes determined by technological scenarios, the calculation of acceptable ranges of parameters used in behavioral scenarios, and the generation of protective rules that control and prevent all oversteppings of behavioral scenarios beyond acceptable boundaries that appear due to incorrect input information, failures and defects [8, 9].

The generation of a technological application basing of a correct detailed model guarantees that there are no unauthorized codes in the application, which contradict the conditions of the correct behaviour of the technological scenario when it is implemented in a network-centric workshop.

4. The main stages of the formalization of technological processes

The main idea of this section is to try to apply and adapt the known network methods for analyzing the network scheduling [10, 11] in relation to the problem of modeling the work of the production site [1, 12]. A difference from the standard methods [13, 14] consists in an attempt to present new set-theoretic formal models of network methods, which allow developing these methods for hierarchical structures, when each operation performed can be a complex one and have its own structure, containing relevant micro-operations, etc.

The whole technological process is reduced to the need to perform a certain set of interdependent actions (operations) (b_i): from the delivery of workpieces and tools from the warehouse to the machines to the transportation of the finished product of a given nomenclature to the warehouse. As a result, a technological table (TT) can be built with the number of rows equal to the number of operations (b_i). Each line indicates on which operations this operation is based (for example, the machine is free, the workpiece and the cutting tool are installed). The latter operations, in turn, are based on other operations (for example, the machine completed processing of the previous workpiece; the adjuster arrived to install the workpiece, etc.). A technique for constructing TTs based on the principle of dynamic programming is proposed. The analysis of the technological chain is carried out "from the end". At the final stage, everything is known: all parts are made and are in the warehouse of finished products. Further, for a specific part to be there, it must be delivered there. The latter is possible, if it was made, removed from the machine and loaded onto a pallet. For this, in turn, it is necessary that the free manipulator remove it from the machine and it was delivered on the free pallet. In turn, the manipulator will be free, if it managed to complete the previous operation, etc. Thus, progress is made from the end to the beginning, which leads to the formation of the TT table.

Using one variation of network methods as a basis, a schedule for the implementation of the technological process is built, and critical paths and critical operations are found thereupon.

A natural criterion for the quality of the implementation of the technological process is the time required for its completion. Network methods allow us to calculate this time taking into account the possibility of parallel execution of certain operations by building a critical path. In addition, this calculates the existing time reserves and critical operations that directly affect the completion time of the entire technological cycle.

4.1. Direct and Inverse Tasks

For a given technological chain (TC) the following tasks can be set:

Direct tasks:

1. Determine the total time of implementation of a given TC and the list of bottlenecks - critical operations.
2. Determine time reserves for all non-critical operations in order to further optimize the TC.
3. Select the most "threatened" operations, which implementation is the most important in a given timeframe.

Inverse tasks (optimization tasks):

1. What amount of additional resources should be allocated so that the total time of the implementation of the TC does not exceed the set value of T_0 , and the additional investments are minimal?
2. Another situation is tied to the redistribution of fixed resources between individual operations in order to minimize the total time of the implementation of the TC (optimal transfer of resources from non-critical operations to critical ones).

3. It may happen that the calculated time T of the TC implementation is less than the specified value of T_0 . How to direct the available time reserve $T_0 - T$ for saving the resources and a corresponding improvement of the technological process?

The inverse tasks make the essence of production site management. They are solved on the basis of algorithms for direct tasks.

4.2. Solution of the direct tasks

Each of the formulated tasks can be formalized and solved by network methods within the framework of the concept of network-centric management, both at the initial design stage of a TC and on the fly. We introduce the necessary notation:

τ_i is the least possible moment of the beginning of the i -th operation b_i , counting from the beginning of the process of the implementation of the TC;

T_i is the least possible moment of the ending of the i -th operation b_i , counting from the beginning of the process of the implementation of the TC. Clearly, $T_i = \tau_i + t_i$.

Using the introduced variables and the initial model of the TC, it is possible to calculate all the times τ_i , T_i of all operations $B = \{b_1, b_2, \dots, b_n\}$. Each set $f(b_i)$ is assigned a number

$\tau_i = \max \{T_{k_1}, T_{k_2}, \dots, T_{k_i}\}$, where $f(b_i) = \max \{b_{k_1}, b_{k_2}, \dots, b_{k_i}\}$. By writing out similar relations for all operations b_1, b_2, \dots, b_n it is possible to obtain the corresponding number sequence $\{\tau_i\}, \{T_i\}, i = 1, 2, \dots, n$. Then, by construction, the total execution time of the given TC will be $T_i = T = \max_i \{T_i\}$. With this information, we can identify the so-called *critical operations* that

determine the completion time of the entire TC. It can be done by following these steps.

Step 1. Find the operation b_i , for which $T_i = T = \max_i \{T_i\}$. The operation b_i will be the first critical operation.

Step 2. Find the corresponding number $\tau_i : \tau_i = \max \{T_{k_1}, T_{k_2}, \dots, T_{k_i}\}$ by the found operation b_i .

Step 3. Find the set of numbers $Arg \max_{k_i} \{T_{k_1}, T_{k_2}, \dots, T_{k_i}\}$.

Operations b_i , on which this maximum is reached, will correspond to the second critical work (works) from the end (there may be several - by the number of maxima of the set $Argmax$).

Step 4. We continue the process until it ends with the exhaustion of the list of operations b_1, b_2, \dots, b_n .

4.3. Solution of the inverse tasks

We formulated three possible basic tasks of optimizing the work of the production site above. They correspond to a certain level of a given complex hierarchical process and belong to the inverse tasks of modeling the process of automating the functioning of a production site. The optimization goals can be formulated thereof and the own inverse tasks can be set for each hierarchical level. Consider one of the inverse tasks.

It is needed to determine what amount of additional resources should be allocated so that the total time of the implementation of the TC does not exceed the set value of T_0 , and the additional investments are minimal.

Let the critical path be found as a result of solving a direct analysis problem $b^k = (b_1^k, b_2^k, \dots, b_m^k)$.

Let the execution time of the whole complex of operations be $T = \sum_{j=1}^m \varphi(b_j^k) > T_0$, where T_0 is the specified time to perform all necessary operations. Process requirements are violated, as it is required that inequality $T \leq T_0$ must be satisfied. However, there are reserves. Reserve models may vary. In this case, we can assume that the allocation of a certain additional resource r_i for the operation b_i reduces the value of the t_i by $\Delta t_i : \Delta t_i = \delta_i(r_i)$, where $\delta = (\delta_1, \delta_2, \dots, \delta_n)$ is the set resource vector function. The number of components of this function is equal to the total number of operations considered at this hierarchical level.

The following natural formulation of the task arises. It is required to choose a resource vector $r = (r_1, r_2, \dots, r_m)$ in a way that, firstly, the inequality $T_r = \sum_{(k)} \{\varphi(b_j) - \delta_j(r_j)\} \leq T_0$ will be satisfied, where the summation is performed on the critical operations of the new critical path, obtained in accordance with the final allocation of additional resources. And secondly, to ensure that the total investment of the resource is minimal: $r = \sum_{i=1}^n r_i \rightarrow \min$.

5. Conclusion

The paper proposes an approach to solving problems of reliable network-centric control of technological processes of the production site of the Internet of things. The technique of reliable solution of the tasks of automation of planning and management of a multiparameter control network, in which it is necessary to ensure a balance between dozens of target performance criteria for various stages of technological processes, is considered. As a result software for net-centric management is implemented and processing time, delays and production cost are estimated. It is planned to implement the solution described at the ship repair workshop.

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