Net-Centric Internet of Things for Industrial Machinery Workshop

Pavel Drobintsev[1], Igor Chernorutsky[1], Vsevolod Kotlyarov[1], Lina Kotlyarova[1], Alexey Tolstoles[1], and Irina Khrustaleva[1]

Peter the Great St.Petersburg Polytechnic University, Saint Petersburg, Russia
vpk@spbstu.ru

Abstract. The most promising way of the development of manufacturing automation systems of the future is usage of the network-based control solutions as their basis. Ideally, these complex net-centric systems should use adaptive approach to planning of the manufacturing scenarios and function with high reliability. There are several issues in this field of work. The first one is that such systems operate on large sets of parameters and are characterized by complex operability modes controlled by a large number of criteria. The second one directed to the small–scale manufacturing is labor intensity of preparation of operative documentation for various technological processes. This paper describes an approach to small-scale manufacturing workshop automation, which can adapt to various technological processes on the fly and effectively use the required resources.

Keywords: Network-centric control · Adaptive manufacturing · Industrial Internet of Things · Multi-criteria manufacturing optimization · Reliable technological processes.

1 Introduction

Today the driving trend of the manufacturing of the future is Industry 4.0. Its core principle is in organizing workshop automation basing on the networking 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 their ability 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].

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

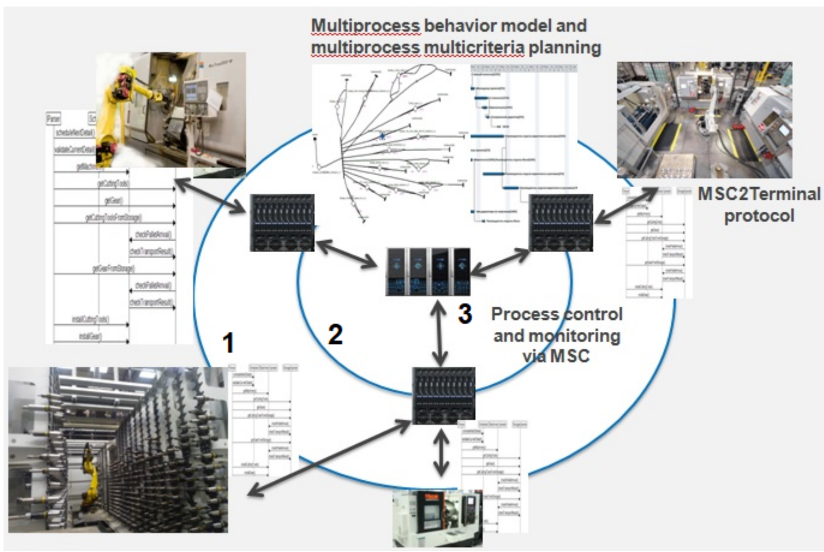


Fig. 1. Machinery workshop with three levels of network-centric control

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

1. The first level works as the base 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 (TPs).

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 in details of single action performed by the machine and instead operate with sequences of single actions which form the so-called macro-operations of, for example, making a surface of a workpiece. Each macro-operation has a set of parameters defining its modes, constraints and conditions.

Macro-operations are transmitted between objects on the first and second control levels. The technologies of making of various details are described in terms of optimized sequences of the macro-operations which satisfy multi-criteria hierarchical optimization from the third control level. The network-centric workshop reliability is ensured in several following ways:

- Technological scenarios. The schedule of the workshop in the form of the description of the set of concurrent behavioral scenarios consists of the conditions of both the usual and alternative behaviors depending on the parameters and domains of the scenarios. With the means of symbolic verification the fullness and resolvability of the behaviors derived from the optimized schedule are proved operatively.
- Transport protocols. The reliability is achieved by monitoring the history of interactions in the technological processes, detection and processing of incorrect incidents.
- Continuous monitoring of the system states.

3 The Approach to Formalization of Technological Processes of the Machinery Workshop

In the single-part and small-scale manufacturing [2] with the decrease of the scale of production follows the trend of reducing the cost of the technological preparations [3].

For the traditional small-scale manufacturing the attempt to decrease the lead time of an order by reducing the degree of detail of technological preparations leads to an increase in the production cycle, as well as to a decrease in the quality of work performance. In addition, the situation with planning is complicated by the fact that the work “under the order” is difficult to predict even for a small perspective, so the volume-calendar plan is a certain forecast based on the statistics of past orders. It is quite natural that such a forecast cannot serve as a basis for the formation of a detailed production plan.

The basis of the methodology for creating such a plan is necessary and sufficient information support with an unambiguous and complete description of the design and technology of the product, as well as the planned loading of each production process object. From the total amount of design information for planning purposes, the product structure and the specification for the assembly units are required, which, when using automated processing in engineering, is made in accordance with GOST 2.053-2006 [4].

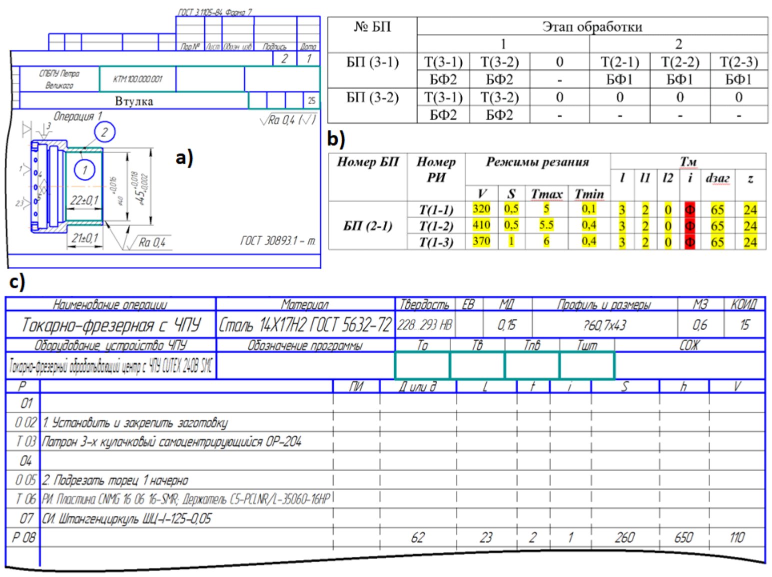
3.1 Features of Solving the Problems of Small-Scale Manufacturing Organization

In the approach proposed in this paper, the described problems were solved due to the following factors:

1. The operative solution of the problem of multi-criteria planning on a supercomputer and operative recalculation of the current schedule of the workshop in accordance with the information on the state of all objects of network-centric production.
2. Usage of features of formalization of technological processes, in which the construction of a set of electronic documentation for technological preparations for the production of the whole product is replaced by the assembly of documentation from the database of its components.

Traditionally, the stage of the technological preparations for production is completed by the development of the so-called operating card which describes the technological sequence of operations (in our case, macro-operations), necessary for manufacturing the product (Fig. 2). Figure 2 shows the layout of the product (a), the fragments of the parameter space tables (b) and the part of the operating card for one part of the detail (c).

The conditions of each technological macro-operation are recalculated based on the exact data from the result of planning. As a result, we get a huge variety of possible options.



№ БП	Этап обработки					
	1			2		
БП (3-1)	T(3-1)	T(3-2)	0	T(2-1)	T(2-2)	T(2-3)
	БФ2	БФ2	-	БФ1	БФ1	БФ1
БП (3-2)	T(3-1)	T(3-2)	0	0	0	0
	БФ2	БФ2	-	-	-	-

Номер БП	Номер РИ	Режимы резания				Тм					
		V	S	Tmax	Tmin	l	l1	l2	i	dзаг	z
БП (2-1)	T(1-1)	320	0,5	5	0,1	3	2	0	Ф	65	24
	T(1-2)	410	0,5	5.5	0,4	3	2	0	Ф	65	24
	T(1-3)	370	1	6	0,4	3	2	0	Ф	65	24

Наименование операции	Материал	Твердость	ЕВ	МД	Профиль и размеры	МЗ	КОИД
Токарно-фрезерная с ЧПУ	Сталь 14Х17Н2 ГОСТ 5632-72	228...293 НВ		0,15	?60,7x43	0,6	15
Оборудование, устройство ЧПУ	Обозначение программы	То	Тв	Тпв	Тшт	СОЖ	
Токарно-фрезерный обрабатывающий центр с ЧПУ CUTEX 240B SMC							

Р		ПИ	Д или д	L	t	i	S	h	V
01									
О 02	1. Установить и закрепить заготовку								
Т 03	Патрон 3-х кулачковый самоцентрирующийся ОР-204								
04									
О 05	2. Подрезать торец 1 начерно								
Т 06	РИ. Пластина CNMG 16 06 16-SMR; Держатель C5-PCLNR/L-35060-16HP								
07	СИ. Штангенциркуль ШЦ-I-125-0,05								
Р 08			62	23	2	1	260	650	110

Fig. 2. Informational basis of the operating card

The proposed approach is based on assembling the technological documentation of the product, for example, the operating card, from the documentation for its typical components. Such components typically are geometric shapes of the surfaces of details: cylinders, cones, parallelepipeds and the like. To process each component its parameters such as the type of workpiece, material, variants of the cutting tools and gear, machining modes, etc. are fixed in the database. The database also fixes the restrictions on the use of the processing modes for each component.

The implementation of the technology fixed in the operating card in network-centric production is the transfer of messages (transactions) from the controller to the object of the operation - machine, robot, automated warehouse or equipment adjuster. On completion of the current operation, the object sends a message to the controller and the request for the next operation. Thus, the implementation of technology is reduced to the exchange of messages in network-centric production. A convenient means of formalizing message exchange for concurrently interacting objects is the standardized MSC language [5]. To encode the macro-operation sequence, it is sufficient to automatically convert the operating card to MSC notation. An example of such a transformation is shown in Fig. 3.

3.2 Features of Planning of Technological Processes

In this paper the planning phase of the technological processes is directed to working on the following tasks [6–10]:

1. The first one is selection of optimal (rational) scenario of TP implementation in accordance with time criteria considering concurrent work of equipment and downtime due to waiting for equipment vacancy after executing previous operations.
2. The second one is determination of resource reserves while executing separate non-critical operations.
3. The third task is to ensure the greatest possible savings of resources in the production of the same product range.

To formalize the technological process and create its appropriate structure, you need to specify a number of sets, such as the set of products of a certain number and the set of resources required for implementation. At the same time, in the general model it is necessary to take into account the possibility of using different workpieces processed on different equipment to produce one finished product.

The whole TP eventually boils down to execution of specific set of standard actions (a_i), from delivery of workpieces and tools from warehouse to machines to transition of produced goods of specific nomenclature to warehouse. Time for all operations is specified. Some operations can be executed simultaneously. Obviously downtime of equipment is not desired. Description of TP and specification of set of operations (a_i) allows setting existing consequence links between separate operations. For example, producing a detail on the machine is impossible without delivery of corresponding workpiece from warehouse. At the same time the machine shall be free (this is also an operation), as well as all required manipulators for delivering and placing of the detail.

Technological table $T(a_i)$ in the form of a matrix where number of rows equals to number of macro operations (a_i) shall be created as a result. Each row indicates what operations this operation is based on (for example, the machine

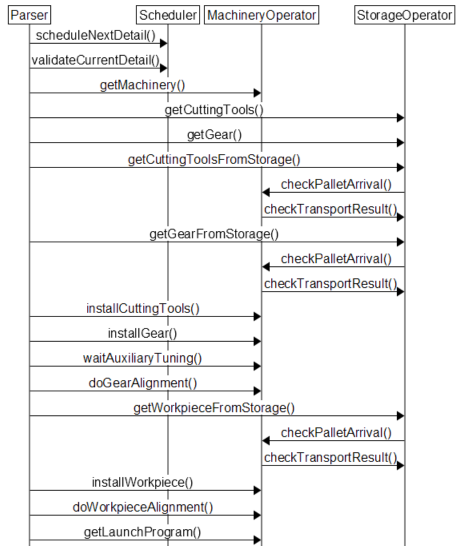


Fig. 3. MSC diagram corresponding to the sequence of macro-operations (the parameters of the messages are omitted)

is free, the workpiece and cutting tools are prepared and installed). Later operations are based on other operations (for example, the machine has finished processing of previous detail, adjuster arrived to set a workpiece, etc.)

Unlike standard approaches to modeling of TP and manufacturing [6–10], network methods allow quite simple creation of the implementation chart of technological process, analysis of the implementation, bottlenecks determination and provision of the ways to optimize manufacturing cycle.

An important quality criterion of technological process implementation is the time required for its complete execution. Network methods allow calculating this time considering possibility of simultaneous execution of some operations and create critical path. At the same time existing reserves of time and critical operations making impact on the overall time of technological process are evaluated. At the same time if some operations do not belong to critical path and have reserves of time, their requirements can be reduced which would save resources.

The most time consuming procedure at planning stage is the procedure of technological table creation. A method of its creation based on principles of dynamic programming is proposed. The idea of the method is the following. Analysis of technological process is performed from its end, i.e. when all details have been produced and placed in the warehouse for produced goods. A detail should be delivered to the warehouse to place it there. This is only possible if it has been processed, taken from the machine and placed on a pallet. For this it has to be taken off by free manipulator and delivered on an empty pallet. Manipulator can only be free if it has completed previous operation and so on. So the process goes from its end to beginning which is required to create table

$T(a_i)$ (Table 1). Each its operation can be started only after the end of the other operations which it relies on (they are listed in the third column). This is the only logical limitation to the process. And many operations can be performed simultaneously. The dashes in the third column mean that these operations are

Table 1. Technological table $T(a_i)$

№	Operation a_i	Operations which it relies on	Execution times t_i of operations a_i
1	a_1	-	t_1
2	a_2	-	t_2
3	a_3	$a_i, ..., a_k$	t_3
4	a_4	$a_j, ..., a_m$	t_4
.	.	.	.
n	a_n	$a_l, ..., a_r$	t_n

independent and can be started at any time. It is assumed that each of the operations relies on operations with lower order numbers. This can always be achieved by proper ordering of operations and their renumbering.

For the given technological process, the following direct optimization tasks can be solved:

1. Determination of the total time for the implementation of the specific process and a list of bottlenecks - its critical operations.
2. Determination of the time reserves for all non-critical operations in order to further optimize the process.
3. Identification of the most "threatened" operations, the performance of which is the most important.

The various goals of optimization are the essence of the planning and management of the workshop. For example, the task may be to minimize the total time for the implementation of the TP by accelerating certain operations with additional investments of necessary reserves. Optimization can be carried out already at the design stage of a given TP. It is obvious that in the first place critical operations are being accelerated. However, in mathematical models of optimization it is necessary to take into account that when the TP is varied during the optimization process, the operations that are not critical in the initial version can become critical and vice versa. The following optimization tasks can be formulated:

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

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

The result of the planning phase is formed as a schedule for work distribution to the resources of the workshop (Fig. 4).

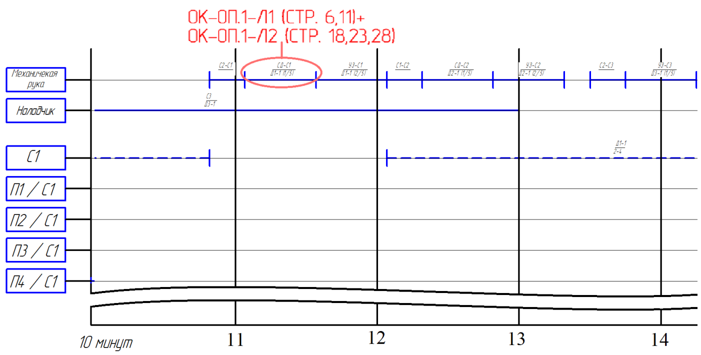


Fig. 4. A part of the schedule for the workshop

3.3 The Procedure for Automating the 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 the 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 their correct behavior [11].
3. Proof of completeness of behavioral technological scenarios in the process of symbolic verification [11, 12].
4. Generation of a set of behavioral scenarios covering all the requirements for the technology description basing on a detailed formal model.
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 [13].
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 [14].

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 behavior of the technological scenario when it is implemented in a network-centric workshop.

4 Usage of the High Performance Computing for Effective Solution of the Automation Tasks

As noted above, the problems of automated planning and management of distributed processes of network-centric manufacturing require significant computing power that can be realized on a high-performance computer. The most obvious possibility to accelerate all the processes of preparation and management of manufacturing is to realize them as parallel. For this, each step in the work of the planning and reliability instruments should be presented in the form of a distributed network of interacting processes. To implement the processes of searching for optimal solutions in a vast space of possible options, verification, generation, analysis and testing, the multi-core cluster of distributed architecture is most suitable.

A rough estimate of the required computational resources is determined by the following:

- The need to select the necessary parameters for cutting tools, workpieces and processing modes. For example, information about the cutting tools and the modes of their use are contained in reference books with thousands of pages, and hundreds of alternatives for a particular option are available.
- Formalization of the technology of processing a workpiece in the form of work on the set of its components requires the ordering and distribution of technological operations into groups that do not require readjustment of the CNC machine. In the process of automated formation of manufacturing technology from stated groups, processing command lists are created with regards to the type of equipment used. As a result, a technology model is prepared for implementation on the unlimited resources of the modeled workshop.
- Planning of real work is executed within the limitations of the workshop resources - machines, automated delivery mechanisms and robots. Moreover, this process takes into account many hierarchically ordered optimality criteria, providing a balance between time and cost of production, equipment loading, stock availability, etc.
- Execution of the created work plan requires continuous monitoring of the states of all workshop equipment and immediate responses (in the form of re-planning of work) to all events related to the violation of the plan.

Since we describe the approach to the implementation of small-scale manufacturing, the tasks of preparation, planning and execution of production work must be solved quickly, ensuring changes in the workshop operations within minutes. This requires organization of joint work for the workshop of 10-15 processing facilities (machines, robots, storage) and about a thousand parallel computing processes.

Theoretically, parallel launching will give linear scalability. However, there are still limits on executing on CPU/server, because machine has limited number of cores/threads. Therefore, you will only have some work running, while the rest of it will wait for its turn. Model of Toolset for planning, Control and Monitoring technology processes was deployed on the Supercomputer of Saint Petersburg State Polytechnic University on Tornado cluster. It has 800+ TFLOPS of peak performance, 656 nodes, each with 2 CPU Xeon E5-2697 v3 and 64 GB of DDR4 RAM. Installed OS is modified CentOS, scheduling engine is SLURM.

5 Conclusion

The proposed approach is developed and tested in the boundaries of the grant on the topic "Theory and technology of design and development of reliable and efficient network-centric management of production processes of the Industrial Internet of Things". As a result, a working prototype of the software complex was created, which is a model of a small-scale workshop. The main solutions and features of the small-scale production workshop in the field of ship repair were verified on the model. The obtained results confirmed the achievement of the main goals formulated in the project. In 2019, it is planned to integrate a software package in the workshop of a shipbuilding enterprise.

Acknowledgments. The work was financially supported by the Ministry of Education and Science of the Russian Federation in the framework of the Federal Targeted Program for Research and Development in Priority Areas of Advancement of the Russian Scientific and Technological Complex for 2014-2020 (№14.584.21.0022, ID RFMEFI58417X0022).

References

1. Abdulbarieva E.I. High-tech computer engineering: a review of markets and technologies. Publishing house of the Polytechnic. University Press, St. Petersburg.
2. Kolesnikova O.V., Lelyukhin V.E. Method of Planning of the Unique Discrete Mechanical Engineering Production // Engineering - from theory to practice: proc. of the XXXVIII int. scientific-practical conf. N 9(34). -– Novosibirsk: SibAC, 2014.
3. Technology of mechanical engineering. Part I: A Tutorial/ A.L. Zhukov, I.I. Kozar, B.Y. Rozovskiy, V.V. Degtyarev, A.M. Soloveychik; Red. by S.L. Murashkina. SPb.: Publishing house of the SPbGTU, 1999. – 190 pp.

4. GOST 2.053-2006. Unified system of design documentation. Electronic structure of the product. General provisions. M. Standardinform. 2007.
5. ITU-T. Recommendation Z.120 : Message Sequence Chart (MSC2000). Geneva, 1999.
6. Chernorutskiy I.G. Optimization Tools in Control Theory, “Piter”, Petersburg, 2004, pp. 256.
7. P. Fritzson, Introduction to Modeling and Simulation of Technical and Physical Systems with Modelica. Wiley-IEEE press, 2011.
8. S. Dong and D. Medeiros, ”Minimizing schedule cost via simulation optimization: an application in pipe manufacturing,” Int J Prod Res, vol. 50, pp. 831-841, 2012.
9. M. Neumann and E. Westkamper, ”Method for Situation-based Modeling and Simulation of Assembly Systems,” Procedia CIRP, vol. 7, pp. 413-418, 2013.
10. M. Neumann, C. Constantinescu and E. Westkamper, ”Method for Multi-Scale Modeling and Simulation of Assembly Systems,” Procedia CIRP, vol. 3, pp. 406-411, 2012.
11. S. Baranov, V. Kotlyarov, A. Letichevsky, P. Drobintsev. The Technology of Automation Verification and Testing in Industrial Projects. // Proc. of St.Petersburg IEEE Chapter, International Conference, May 18-21, St.Petersburg, Russia, 2005 -– pp. 81-86.
12. A. Letichevsky, J. Kapitonova, A. Letichevsky Jr., V. Volkov, S. Baranov, V. Kotlyarov, T. Weigert. Basic Protocols, Message Sequence Charts, and the Verification of Requirements Specifications. Proc. of ISSRE04 Workshop on Integrated-reliability with Telecommunications and UML Languages (ISSRE04:WITUL), 02 Nov 2004: IRISA Rennes France.
13. I. Anureev, S. Baranov, and others. Tools for supporting integrated technology of analysis and verification of specifications for telecommunication applications // SPIIRAN works – 2013-N1-28P.
14. Drobintsev P., Kotlyarov V., Letichevsky A., Nikiforov I., Peschanenko V. Approach to Behavior Scenarios Debugging Automatic Control and Computer Sciences. 2015. vol. 49. N 7. pp. 430-436.