

The Concept of Flexible Manufacturing System for a Newly Forming Robotic Enterprises

Vladimir Serebrenny, *Member, IAENG*, Dmitry Lapin, *Member, IAENG*,
Alisa Mokaeva, *Member, IAENG*

Abstract— This paper is aimed to form the concept of the perspective manufacturing system for newly forming hi-tech robotic enterprises. Small innovative enterprises and large production centers on the stage of modernization are typical companies in terms of the systems mentioned above. An analysis of transition requirements to Industry 4.0 under the program 'National technology initiative' and features of newly forming robotic enterprises was made. An overview of the perspective manufacturing systems was highlighted, the principles of structures forming and functioning mechanisms were shown. The concept of a predictive manufacturing system was suggested. It is based on the mutual integration of two entities: the heterogeneous multi-agent system with the coalitions forming mechanism and the scalable technology of end-to-end identification of complex technical systems. Primary detailing was carried out, highlighting possible advantages and disadvantages of the concept. Conclusions have been drawn about the development perspective of the studies in this direction to set future objectives.

Index Terms— manufacturing system, multiagent system, identification, robotic manufacturing, robotic enterprise

I. INTRODUCTION

WE are witnessing the basic principles and modern technologies laying on the fourth industrial revolution [1, 2] are being implemented. A special place in this issue is occupied by the question of flexible manufacturing systems (FMS) that replaced traditional ones. The essence of FMS is considered as the ability to effectively produce hi-tech goods and services and rapidly react to customers' needs.

Countries all over the globe have their own ways to implement the Industry 4.0 paradigm. Principles of the Russian national technology initiative (NTI) were taken as the basis for this study. In particular, cross-market and cross-industry focus area TechNet [3] that provides technological support for the development of NTI markets and hi-tech industries by forming Factories of the Future [3].

The question of Perspective manufacturing systems (PMS) implementing is one of the key technological barriers. However, assuming the universal properties of the

above-mentioned manufacturing systems, the question arises of the high efficiency and synergy of the system deployment on the specific platforms taking into account special technical and economic circumstances.

The goal of the study is the development of the specialized perspective manufacturing system for the newly forming robotic enterprises. Following tasks have to be done:

- to estimate initial conditions of the newly forming robotic enterprises for further integration;
- to analyze existing PMS and highlight their essential features and properties;
- to form the concept of PMS for the newly forming robotic enterprises, its structure, and operating mechanisms.
- to detail substantive organization and observation subsystems.

II. BACKGROUND

In this paragraph, basic definitions and structures are shown to clarify the prerequisites of the concept formation. According to the NTI concept, one of the advanced manufacturing technologies are:

- industrial sensing: smart sensing and control systems embedded into manufacturing equipment, shop floor or factory;
- industrial robotics: primarily flexible manufacturing cells;
- enterprise information systems: Industrial Control Systems (ICS), Manufacturing Execution Systems (MES), Enterprise Resource Planning (ERP), Enterprise Application Software (EAS).

A. Factories of the Future

The overall concept of the Factories of the Future in according to the extract from of TechNet NTI justifying materials is as follows [3].

A factory of the future is a certain kind of business process, a method of combining business processes, with following features:

- creating digital platforms which are a kind of ecosystems of advanced digital technologies. By leveraging predictive analytics and big data, the platform approach enables integration of spatially distributed designers and manufacturers, and allows to increase flexibility and customization while fulfilling customer requests;
- developing a system of digital models of both newly designed products and production processes. Digital models must have a high level of adequacy to physical products and actual processes enabling the convergence of

Manuscript received April 17, 2019; revised April 19, 2019.

Ph. D. V. V. Serebrenny is with the Bauman Moscow State Technical University, Moscow, 105005 Russia (e-mail: vsereb@bmstu.ru).

D. V. Lapin is with the Bauman Moscow State Technical University, Moscow, 105005 Russia (corresponding author phone +79150556452; e-mail: lapindv@bmstu.ru).

A. A. Mokaeva is with the Bauman Moscow State Technical University, Moscow, 105005 Russia (e-mail: ahm.alisa@gmail.com).

the physical and digital worlds to generate synergy effects;
-- digitalization of the entire product lifecycle, from concept and design to production, use, after-sales service, and recycling. The later changes to a product in the lifecycle are made, the higher are the costs due to those changes. Investing more up front to get the design correct moves changes to an earlier point in the lifecycle where they are less expensive. The qualities of a product that make it globally competitive and appealing to consumers are also determined early in the product lifecycle, during the design phase before a physical representation is produced.

If taken separately, none of the advanced manufacturing technologies can provide a long-term competitive advantage in the market. Complex technological solutions are therefore needed to design and manufacture a new generation of globally competitive products in the shortest time possible. These solutions made up of the best world-class technologies are referred to in the TechNet Roadmap as Digital, Smart, Virtual Factories of the Future and its interconnection (fig. 1).

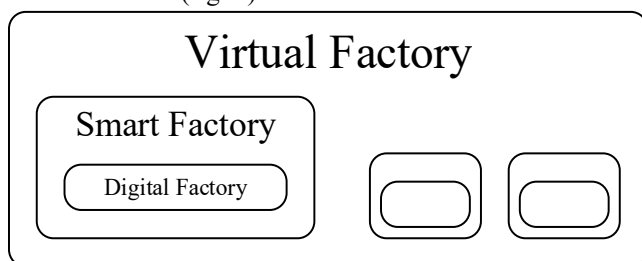


Fig. 1. Interconnection of the structures of Factories of the Future

Digital Factories

Digital Factories are complex technological solutions that ensure the design and manufacture of globally competitive next-generation products in the shortest time possible. They span the product lifecycle from the R&D and product planning stage, where product basic characteristics are laid down, through the development of a digital mock-up (DMU) and digital twin up to making prototypes and small-batch production (paperless production, digital thread). A Digital Factory entails smart models of products (e.g. machines, structures, units, instruments, installations, etc.) developed through the application of the new paradigm of digital design and simulation called 'Smart Digital Twin - (Simulation & Optimization) Smart Big Data-Driven Advanced (Design & Manufacturing)'.

Smart Factories

Smart Factories are complex technological solutions that ensure the manufacture of globally competitive next-generation products from a workpiece to finished part in the shortest time possible. Smart manufacturing is distinctive in that it provides a high level of automation and robotics which drastically reduce quality losses due to human errors (unmanned production). Smart Factories usually use digital mock-ups, digital twins and prototypes developed by Digital Factories. A Smart Factory entails manufacturing equipment - machine tools with computer numerical control, industrial robots, etc. - as well as industrial control systems (ICS) and manufacturing

execution systems (MES).

Virtual Factories

Virtual Factories are complex technological solutions that ensure the design and manufacture of globally competitive next-generation products in the shortest time possible by linking Digital and/or Smart Factories into a distributed network. A Virtual Factory entails enterprise application software (EAS) which allows to develop and use virtual models of organizational, technological, logistical and other processes as a single object at the level of global supply chains (supply, production, distribution and logistics, sales, after-sales service) and/or at the level of distributed production assets.

For the newly forming robotic enterprises, it is common to use Digital Factory and Smart Factory structures features.

B. Newly forming Robotics Enterprises

The newly forming robotic enterprises are part of the technological business development [3]. There are two scenarios of their elaboration: creation from scratch and modification of the existing production. Consider these scenarios in more detail. They will define the key technological solutions and form requirements for effective manufacturing system.

Creation enterprise from scratch

This scenario means the production deployment by small innovative enterprises [4]. The following technical and economic factors are characteristic for the development of this manufacturing:

- small batches of the product;
- a small number of tools;
- small areas of location;
- rapidly changing product.

Assuming these it is possible to conclude the following:

- risks are related to the absence of observation because of space and resource economy.

Modification of the traditional manufacturing

This scenario means partial or full production deployment on the base of medium-sized innovative enterprises and large production centers [5]. The following technical and economic factors are characteristic for the development of this manufacturing:

- large batches of the product;
- a large number of tools;
- large areas of location;
- temperately changing product.

Assuming these it is possible to conclude the following:

- risks are related to the absence of organization because of difficulties of integration in existing system.

C. Critical technologies

There are the following critical technological solutions for each type of enterprise:

- collaborative robotics [6];
- big data [7];
- sets of sensors;

The high intelligence level of the modern tools also impacts on the concept in the questions of effective use of

intelligent elements of these solutions at all levels of management.

D. Technical and economic factors

In both cases, minimizing risks and achieving high efficiency can be reached by implementing lean principles. Proven principles of lean – such as reducing waste in the form of machine breakdowns or non-value-adding activities – will remain fundamental. At the same time, advancements in data collection, sensors, robotics and automation, new technologies and increased computing power will enable advanced analytics and give established methods a new edge [8].

In this, the most rational way is to establish the concept aimed at solving the main problems of the above-described enterprises: formation of the flexible manufacturing organizing system, introduction of universal scalable observation system and as the result of their interaction - control system, based on reconfigurable manufacturing systems approach [9] with the development perspectives to adaptive manufacturing system [10].

III. ANALYSIS

To enable efficient use of the data available in Industry 4.0 oriented processes, it becomes necessary to adapt the control architecture in order to make it flexible, reactive and adaptable enough to reach the objectives previously described. For the last 20 years, Holonic Control Architectures (HCA) has been widely studied and developed. The use at the industrial level is starting to spread due to their effectiveness. A Holonic Control Architecture (HCA) is an architecture composed of holons, called holarchy. A holon is a communicating decisional entity (with inputs and outputs) composed of a set of sub-level holons and at the same time, part of a wider organization composed of higher-level holons (recursive, called the Janus effect [11]). It is important to note that a holon is also composed of a physical part associated to a digital one (that can be modeled as a digital agent, avatar, digital twin) and finally, holons are able to decide according to a certain degree of autonomy [12].

Dynamic HCA are interesting because they integrate an optimal scheduling module used in the normal state, coupled with reactive abilities, executed when a disturbance occurs. When it happens, the HCA may modify its own organization to minimize the impact of this disturbance. Such architectures guarantee that performances of the manufacturing system are optimal in the normal state, but not always in degraded mode.

A. ORCA-FMS

In the manufacturing domain, ORCA – dynamic and heterogeneous hybrid Architecture for Optimized and Reactive Control – [13] was one of the first dynamic HCA that was formalized in literature. ORCA is divided into three layers: the physical system (PS) layer, the local control (LC) one, and the global control (GC) one. The GC has a global view of the system and is composed of one global optimizer. Its role is to guarantee good performances based on the PS's initial state. The LC is composed of many local optimizers, which have a local view of the system only. Their goal is to react to

unexpected events that occur on the PS by making rapid decisions online, thus providing a feasible solution that is suitable for the current system state. Each local optimizer in LC is associated with a physical part in PS. Both the physical part and the local optimizer constitute one entity (fig. 2).

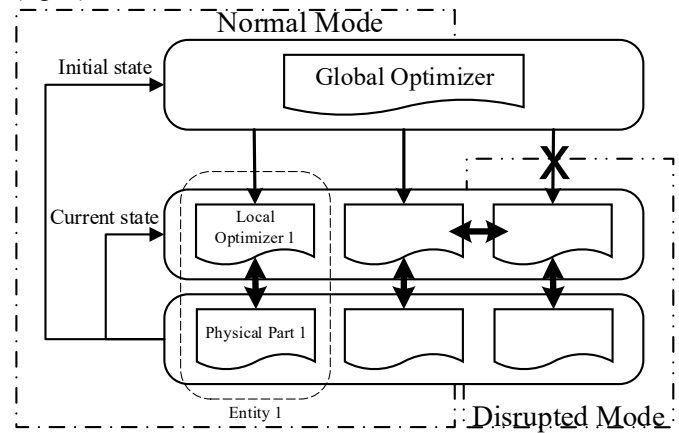


Fig. 2. ORCA global organization

B. ADACOR

ADACOR (ADaptive holonic Control aRchitecture) is a holonic reference for the distributed manufacturing system [14]. ADACOR is a decentralized control architecture but it also considers centralization in order to tend to global optimization of the system. Holons are belonging to the following classes: Product Holons (ProdH), Task Holons (TH), Operation Holons (OpH) and Supervisor Holons (SupH).

An evolution of ADACOR mechanism has also been presented as ADACOR2 [15]. The objective is to let the system evolving dynamically through configurations discovered online, and not only between a stationary and one transient state. The rest of the architecture is nevertheless quite similar to ADACOR. (fig. 3).

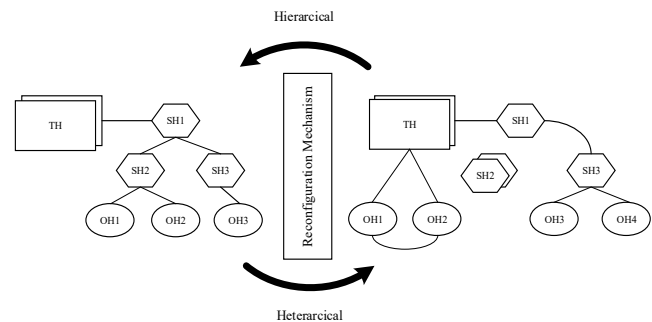


Fig. 3. ADACOR/ADACOR² evolution

C. POLLUX

The last architecture in date is denoted as POLLUX [16] (fig. 4). The main novelty is focused on the adaptation mechanism of the architecture, using governance parameters that enlarge or constraint the behavior of the low-level holons regarding the disturbances observed by the higher level, the idea is to find the “best” architecture that suits detected disturbances. It is a Hybrid Control Architecture (HCA) presented as a reference control system that supports the switching process of the control system between hierarchical and heterarchical architectures.

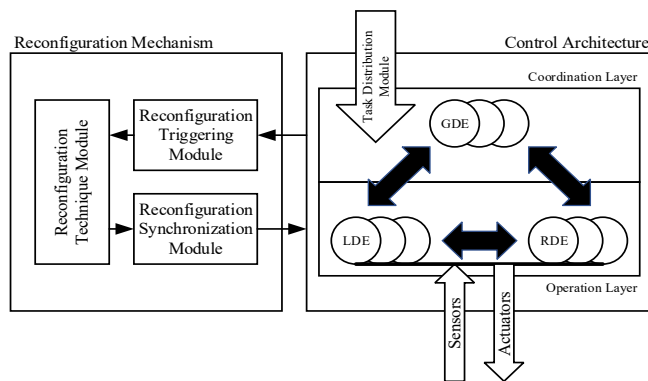


Fig. 4. POLLUX mechanism

IV. CONCEPT

In comparison with the above-mentioned PMS the concept of the manufacturing system is proposed.

A. Description

The system is based on dynamic organizing and observation subsystems. Subsystems implementation and their interaction mechanisms are shown on fig. 5.

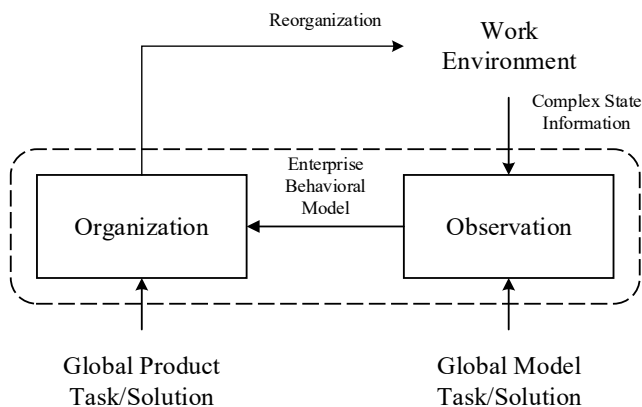


Fig. 5. Subsystems implementation and their interaction mechanisms

This effect is achieved due to the implementation features of the organizing and monitoring subsystems.

Organizing subsystem is based on the multiagent systems approach, observing subsystem – end-to-end structural and parametric identification tool.

B. Structure and Mechanism

The overall structure of the proposed production system is based on two subsystems that carry out both independent functioning and mutual influence. The total effect of adaptive management is due to the effective decomposition of the global task, as well as through the continuous exchange of information at all levels of control (fig. 6).

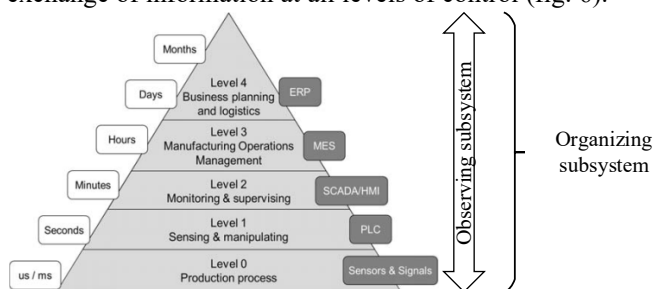


Fig. 6. Coverage of management levels

Subsystems exchange mechanism is based on complex behavioral model of the enterprise (fig. 5). The main object in the behavioral setting is the “behavior” – the set of all signals compatible with the system. An important feature of this approach is that it does not distinguish a priority between input and output variables. Apart from putting system theory and control on a rigorous basis, the behavioral approach unified the existing approaches and brought new results on controllability for nD systems, control via interconnection, and system identification [17].

V. DETAILING

This paragraph describes a more detailed consideration of the organizing and monitoring subsystems structures.

A. Multiagent system

The system used to organize manufacturing tools is a multi-agent group control system, that use a dynamic mechanism of homogeneous and/or heterogeneous coalitions formation [18, 19]. The implementation of such a mechanism brings the system closer to the hybrid control architecture. However, system formation rules are associated with the identification tool result in interpretation in real-time.

The analysis of the modern multiagent architectures showed, that of greatest interest is the coalition model of the system, the essence of which lies in the formation of subgroups of agents. Each group may be considered as a separate self-sufficient system, and as part of the global system. For example, homogenous coalitions are good in a quick readjusting of the production line, heterogeneous - with the selected manufacturing process (fig. 7).

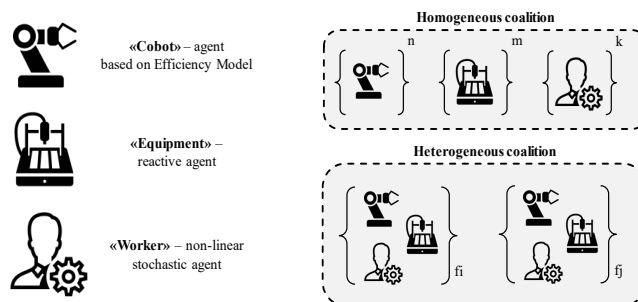


Fig. 7. Types of agents and coalitions

B. Identification tools

The system used to observe manufacturing tools is an end-to-end structural and parametric identification tool. The math part based on wavelet transforms theory.

Wavelet transforms of the input and output parameters [20, 21] are proposed for organizing tools for end-to-end processes identification (fig. 8).

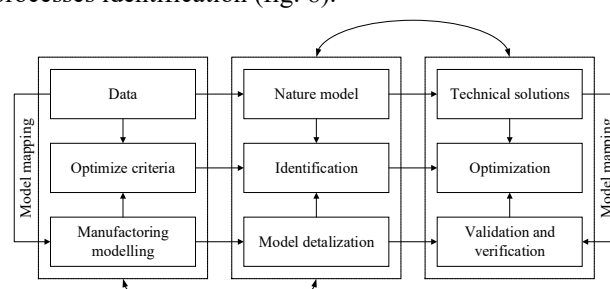


Fig. 8. Complex identification tool

Using the real-time representation of the system in the combined time-frequency domain it is possible to critically evaluate linear and non-linear processes in the system as well as obtaining interpretable information about the real generalized structure and parameters of the system

VI. CONCLUSION

Assuming the results of this study it is possible to conclude the following:

-- the concept of the perspective manufacturing system for the newly forming robotic enterprises meet the modern requirements and technological barriers of the National development program;

-- the key difference from the previously developed PMS is the desire for local efficiency in a particular type of robotic enterprises;

-- the use of combined advantages of the organization and observation subsystems allows achieving a synergistic effect.

The future work will consist of system specification for further software and hardware implementation.

REFERENCES

- [1] Kagermann et al. Umsetzungsempfehlungen für das Zukunftsprojekt Industrie 4.0. (2018, December, 23). Retrieved from https://www.bmbf.de/files/Umsetzungsempfehlungen_Industrie4_0.pdf.
- [2] Tarassov, V. B. (2018, September). Enterprise Total Agentification as a Way to Industry 4.0: Forming Artificial Societies via Goal-Resource Networks. In *International Conference on Intelligent Information Technologies for Industry* (pp. 26-40). Springer, Cham.
- [3] TechNet booklet. (2018, March, 7). Retrieved from http://assets.fea.ru/uploads/fea/nti/docs/TechNET_booklet_ENG_web%20version_2018_02_07.pdf.
- [4] Bi, Z. M., Liu, Y., Baumgartner, B., Culver, E., Sorokin, J. N., Peters, A., ... & O'Shaughnessey, S. (2015). Reusing industrial robots to achieve sustainability in small and medium-sized enterprises (SMEs). *Industrial Robot: An International Journal*, 42(3), 264-273.
- [5] Hedelind, M., & Jackson, M. (2011). How to improve the use of industrial robots in lean manufacturing systems. *Journal of Manufacturing Technology Management*, 22(7), 891-905.
- [6] Vysocky, A., & Novak, P. (2016). Human-Robot collaboration in industry. *MM Science Journal*, 9(2), 903-906.
- [7] Lee, J., Bagheri, B., & Kao, H. A. (2014, July). Recent advances and trends of cyber-physical systems and big data analytics in industrial informatics. In *International proceeding of int conference on industrial informatics* (INDIN) (pp. 1-6).
- [8] Behrendt, A., Müller, N., Odenwälder, P., & Schmitz, C. (2017). Industry 4.0 demystified—lean's next level. Retrieved March, 3, 2017.
- [9] Koren, Y., Heisel, U., Jovane, F., Moriwaki, T., Pritschow, G., Ulsoy, G., & Van Brussel, H. (1999). Reconfigurable manufacturing systems. *CIRP annals*, 48(2), 527-540.
- [10] Keddis, N., Kainz, G., Buckl, C., & Knoll, A. (2013, February). Towards adaptable manufacturing systems. In *2013 IEEE International Conference on Industrial Technology (ICIT)* (pp. 1410-1415). IEEE.
- [11] Koestler, A. (1978). *Der Mensch-Irrläufer der Evolution*. Bern München: Scherz.
- [12] Babiceanu, R. F., & Chen, F. F. (2006). Development and applications of holonic manufacturing systems: a survey. *Journal of Intelligent Manufacturing*, 17(1), 111-131.
- [13] Pach, C., Berger, T., Bonte, T., & Trentesaux, D. (2014). ORCA-FMS: a dynamic architecture for the optimized and reactive control of flexible manufacturing scheduling. *Computers in Industry*, 65(4), 706-720.
- [14] Leitão, P., & Restivo, F. (2006). ADACOR: A holonic architecture for agile and adaptive manufacturing control. *Computers in industry*, 57(2), 121-130.
- [15] Barbosa, J., Leitão, P., Adam, E., & Trentesaux, D. (2015). Dynamic self-organization in holonic multi-agent manufacturing systems: The ADACOR evolution. *Computers in industry*, 66, 99-111.
- [16] Jimenez, J. F., Bekrar, A., Zambrano-Rey, G., Trentesaux, D., & Leitão, P. (2017). Pollux: a dynamic hybrid control architecture for flexible job shop systems. *International Journal of Production Research*, 55(15), 4229-4247.
- [17] Markovsky, I., Willems, J. C., Van Huffel, S., & De Moor, B. (2006). *Exact and approximate modeling of linear systems: A behavioral approach* (Vol. 11). SIAM.
- [18] Vorotnikov, S., Ermishin, K., Nazarova, A., & Yuschenko, A. (2018, September). Multi-agent Robotic Systems in Collaborative Robotics. In *International Conference on Interactive Collaborative Robotics* (pp. 270-279). Springer, Cham.
- [19] Pechoucek, M., Marik, V., & Stepankova, O. (2000). Coalition formation in manufacturing multi-agent systems. In *Proceedings 11th International Workshop on Database and Expert Systems Applications* (pp. 241-246). IEEE.
- [20] Bakhtadze, N., & Sakrutina, E. (2016, May). Wavelet-based identification and control of variable structure systems. In *2016 International Siberian Conference on Control and Communications (SIBCON)* (pp. 1-6). IEEE.
- [21] Bakhtadze, N., & Sakrutina, E. (2016). Applying the Multi-Scale Wavelet-Transform to the Identification of Non-linear Time-varying Plants. *IFAC-PapersOnLine*, 49(12), 1927-1932.