System and Structural Approach to Interaction of Components in Collaborative Flexible Production Systems

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***Abstract* – The paper analyses a well-known representation of the automation process as a hierarchical structure in the form of a five-level pyramid with levels 0, 1, 2, 3, 4. The analysis is based on the essence of the concepts "system", "structure", "collaborative industrial robot" (CIR), "collaborative flexible production system" (CFPS). It is proposed to introduce an additional sub-level 0-1, which occupies an intermediate position between the lower levels 0 and 1. It is this sub-level that is reproduced from the standpoint of its structure, considered as a system and meaningfully interpreted as an integral component of the Human-Robot Collaborative System (HRCS). The interaction of Human (H) and CIR is the basis of the execution of technological operations common to H and CIR, which is the content of the collaboration phenomenon. It is sub-level 0-1, called the Human Factor Level, that reproduces collaborativeness and is considered as the Human Robot Collaborative Level (HRCL), which takes into account and reveals the internal connections of this sub-level.**

The analysis of the presented structure content and the relationships between the components of the HRLC made it possible to interpret it as implementing the executive-hardware-controlling component of automation. This interpretation of its content makes it possible to formalize the connections between its components, which determine the obvious directions of research into the phenomenon of collaboration. The formalization of scientific and practical research is presented, which meaningfully reproduces both the collaborative component of automation and its traditional (non-collaborative) component. Directions for further research are determined.

***Index Terms*—robot, collaborative robot**

I. Introduction

Today, the rate of robotics development and its application in industrial production and in other areas of human activity is steadily increasing. This is due to the general technological progress and the development of microprocessor technology, which allows the application of more advanced and flexible methods of industrial robot control (IR). Modern trends in the development of robotics in general indicate a significant increase in the production and use of a special type of IR in modern technological productions, namely collaborative industrial robots (CIR) [1]. CIR is a type of IR developed to perform various technological tasks in collaboration with workers (people) in production sectors [2]. The main feature of CIR is the flexibility of application in cooperation with a person, which makes it possible to use this type of technological equipment in various areas of production, starting with the automotive and ending with the food industry. There is also the practice of using CIR in non-production areas, for example, in medicine [3], in post office warehouses in cargo and sorting areas [4], etc.

The increase in the scope of CIR application often causes the problem of understanding and complying with ISO safety standards, standardization and interpretation of terms and choosing the methodology for developing work algorithms at the stage of technological preparation of robotic productions.

Currently, CIRs are divided into two conditional groups. The first group of CIR meets the requirements of ISO 10218-1, and the second group does not meet the general safety requirements of ISO, but meets the requirements of other standards [2].

The authors interprite the term system-structural approach as the study of an object as a whole set of elements in a set of relationships and connections between them, that is, the object is considered as a system [5].

On the basis of [6], the authors understand the structure as an integral object that contains a set of elements with their connections (relations). And the system, in turn, is considered as a structure that interacts with the environment and internal elements [7].

In this paper the authors regard the term collaborative flexible manufacturing systems (CFMS) as a well-known definition of FMS, in which CIR is used as a universal flexible means of automation.

Considering the above mentioned, an important aspect in the work of a human being with CIR, as well as with the main and auxiliary technological equipment, is the definition of terminology and general safety principles that would meet ISO and other standards that take into account the essence of the system-structural approach. The above mentioned is not possible without identifying and formalizing the components of technical and technological systems and the connections (relationships) between them.

II. Literature Review

According to the IFR, the annual increase in the production and sale of IR is constantly growing [1]. This indicates that modern technological production increasingly uses IRs as technological equipment, which are considered as universal flexible means of automation.

There is a well-known work that highlights the problems of using CIR in collaboration with a human (H) in assembly technological processes (TP) [8]. The authors describe the

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methodology of dynamic distribution of technological operations between Cobot (Collaborative Robot) and H, based on various data, such as equipment parameters, features of TP and collaborative workspace, etc. The above mentioned indicates the existing problems of using CIR in industry and suggests a methodology for improving the productivity of CIR cooperation with humans. However, this study does not consider this problem from the point of view of systematicity and structural representation of its components.

Paper [9] considers the problem of the efficiency of CIR automated lines, which perform assembly operations. The authors developed a mathematical model of an automated line with CIR for a real production situation. The research results showed the economic benefit of CIR for automation in production facilities using manual work. However, this work does not structurally consider the problem of the H-CIR system.

The content of work [10] is the analysis of CIR successful application in assembly processes. The researchers considered the manufacturing process of a part of the pneumatic cylinder type in the H-CIR system. Based on the research, the authors proposed methods for integrating CIR into production systems with assembly processes. This work deeply considers the collaboration of CIR with a human in a real assembly TP, it defines and describes the parameters of this process, but does not consider the systemic and structural representation of the production sector with CIR and does not highlight the connections between CIR and H.

Work [11] indicates that CIR is part of a modern automated system within Industry 4.0. The authors of this article analyze three successful industrial examples of CIR implementation and highlight the main issues based on empirical data. Researchers use this information to identify key factors to consider when designing an industrial work system using collaboration jf a human and CIR.

The content of work [12] indicates the existing problems of security and effective application of CIR in Industry 4.0 systems. Its disadvantage is the lack of a system-structural analysis of the automation pyramid certain levels.

The above provisions were reflected and developed, as well as their drawbacks, in Industry 5.0 trends [13]. This indicates the relevance and expediency of conducting research in the field of collaborative robotics.

A generalized analysis of the given information sources indicates insufficient detailing of inter-level components and absence of formalized connections and relations between them.

Therefore, in this work, the authors consider it expedient to systematically approach the analysis of the pyramidal representation of automation in order to differentiate and clarify its components, interaction and connections between them. Therefore, the simplest, from the authors' point of view, auxiliary block 0-1 (Fig. 2) is considered as an intermediate sublevel between levels 0 and 1. It is the systematic and complex consideration of it that makes it possible to further formally determine the connections between the main components of the CFMS. The above mentioned determines the systematic conduct of research at the so-called executive-hardware-controlling level of automation. This, in turn, makes it possible to systematize and formalize such research and conduct it in an orderly manner.

Therefore, the purpose of this work is as follows: to perform a structural analysis of the lower levels of automation based on the content of the well-known representation of automation as a hierarchical multi-level pyramid; to propose an additional intermediate sub-level that reproduces the executive-hardware-controlling component of the automation process and its collaborative nature and enables us to formally present the directions of scientific research, which take into account the essence and peculiarities of collaborative industrial robots functioning.

III. AUTOMATION PYRAMID AND HUMAN IMPACT

Modern technological manufacturing can be structurally described using the so-called automation pyramid (Fig. 1) [14].

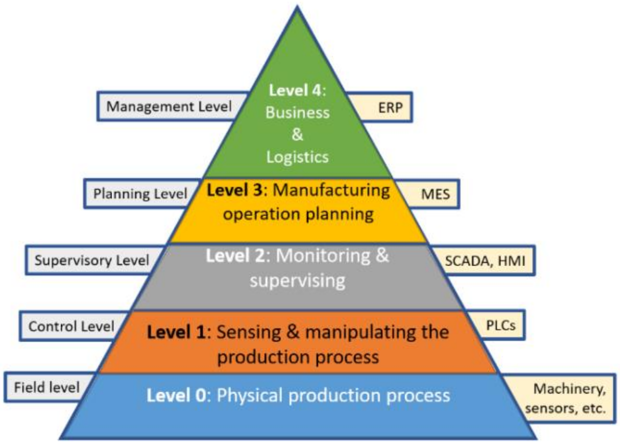

Fig. 1. Automation Pyramid according to ISA 95 model [14]

This graphic automation level structure represents each technical, economic and managerial part of production, starting from sensors and ending with the planning and management department. Usually, the classic structure of automation is described by five levels, namely 0, 1, 2, 3, 4, which mean

0 – Field (measuring, actuating, communication);

1 – Control (PLC – Programmable Logic Controller);

2 – Supervisory (SCADA – Supervisory Control And Data Acquisition);

3 – Planning (MES – Manufacturing Execution System);

4 – Management (ERP – Enterprise Resource Planning).

Each of these automation pyramid levels describes the main elements of classic automated production. The authors of this work focus on insufficient detail in terms of organization and systematization of levels 0 and 1, where, in the traditional sense of automation, almost all processes are performed automatically, and human functions consist in monitoring and controlling the process. However, the above-mentioned structural representation of automation (Fig. 1) cannot fully describe production sectors with CIR, where people are direct participants in TP, and not simple observers.

It is appropriate to emphasize that the two lower levels of the automation pyramid, namely Control (PLC) level (level 1) and Field level (level 0) can be considered as those that meaningfully, structurally and systematically (at a certain level of abstraction) form a Human-Robot collaborative system (HRCS).

The current state of terminology and ISO safety standards do not fully determine the content of the peculiarities of CIR with H application in production. Many statements and instructions are of a recommendatory nature and do not provide an algorithm for the actions of the Human-Robot (H-R) technical-technological system components in individual production situations.

Such a vague, blurred situation gives rise to a number of fundamental questions regarding collaborative robotics in various fields of production. One of the basic issues is the determination of the CIR application effectiveness in a pair with a human, for example, the determination of productivity, the safety of a collaborative human-robot system, etc.

The inclusion of a special sub-level 0-1 in the automation pyramid presents the automation in the production sector using CIR in more detail and more holistically. It necessarily indicates the peculiarity of collaborative robotics and to some extent specifies the human factor. This sub-level 0-1 describes the interaction of workers as a component of the technical-technological system using CIR and technological equipment (Fig. 2), expanding and clarifying the HRCS mentioned above.

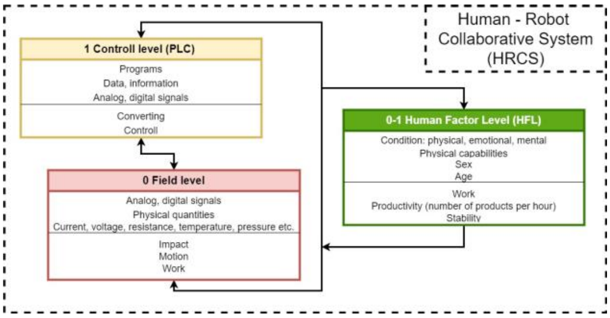

Fig. 2. Structural representation of HRCS with the introduced HFL sublevel

The above interpretation and graphic representation of HRCS presents a part of the automation pyramid in terms of collaboration of CIR and technological equipment with H.

The introduction of the HRCS intermediate component is the sublevel 0-1 Human factor level, which accentuates the complex representation of a human as an integral HRCS component with certain parameters and features of his work. Connections between levels 0 and 1 in physical terms can be represented, for example, in the form of analog and/or digital electrical signals. The connections between the Control (PLC) level and the Field level are interdependent and have the feedback (see below). However, it is obvious that the Control (PLC) level in the context of its functionality is the main one in this hierarchy. Block 0-1 Human Factor Level is connected to other blocks by connections that contain information of different content and origin. Examples of this are the physical influence of H on the CIR, which is converted into an electrical signal in the joints of the CIR links, for example, during collisions. The software influence of the H on the CIR is performed directly from the CIR remote control system, It is of electrical nature, analog and/or digital type and it implements corresponding CIR actions with / without intermediate information transformations. Therefore, each HFL block is conceptually divided into two parts. Block 0-1 Human Factor Level highlights some basic parameters of employees from the point of view of influence on TP in part of its collaborative component. First of all, it is the physical, emotional and psychological state of employees. The above mentioned conditions are responsible for the main indicators of the workers' bodies and their functioning. This affects the reaction, endurance, stability of the work of employees, etc. The parameter "physical capabilities" describes the strength, speed and other qualitative and quantitative parameters of a specific individual, which affects the performance of the HRCS as a whole. "Age" and "gender" directly affect the specific types and parameters of technological operations performed by employees in HRCS as well as their productivity. This structure highlights the idea of functional-technological production integrity of a human, hardware and software part in HRCS.

The content and complex analysis of levels 0 (Field Level), 1 (Control Level) and sub-level 0-1 (HFL) made it possible to transform the specified HRCS components into the so-called HRCL block, i.e. Human Robot Collaborative Level (Fig. 3). The components of HRCL include indicators and parameters of its two parts, namely Human and Collaborative Robot.

The above presented data provides an opportunity to analyze sublevel 0-1 from the standpoint of systematicity and complexity. This, in turn, makes it possible to systematically consider options (types) of interaction between HRCL components, namely between H, CIR, Intelligent Assist Devices (IAD) [15] and other technological (industrial) equipment (IE).

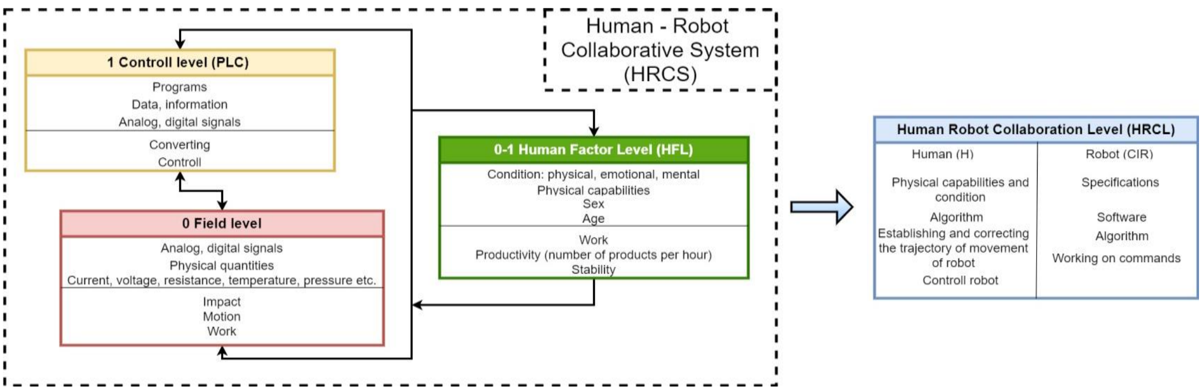

Fig. 3. Scheme of levels 0, 1 and sublevel 0-1 transformation in HRLC

IV. Human Robot Collaboration Level

The indicators and features of H are characterized by the physical capabilities and possible reaction algorithms when H interacts with CIR, while establishing and correcting trajectory movements with a gripper through the appropriate reaction of the CIR control system to external stimuli, which are, for example, collisional, etc.

Summarizing the components of HRCL and their functionality, the authors developed a graphical diagram of of sublevel 0-1 components functioning of (Fig. 4).

Fig. 4 shows that the HRCL includes two types of components: Mandatory Components (HRCSMC) and Optional Components (HRCSOC). HRCSMC includes well-known components H and CIR, and HRCSOC includes such components as IAD, i.e. Intelligent Assist Devices (IAD) and IE, i.e. other technological (industrial) equipment, for example, devices for orientation, transportation, etc.

Fig. 3. Scheme of levels 0, 1 and sublevel 0-1 transformation in HRLC

In Fig. 4, symbol (x) denotes the Cartesian product of the corresponding components when reproducing their interaction, and symbols α^c and α denote those meaningful studies that correspond to their collaborative and "traditional" components, respectively.

At the same time, taking into account a certain level of abstraction, four main directions of research are highlighted for α^c (expressions (1), (2), (3), (4)) and three for α (expressions (5), (6), (7)). The latter directions are better studied and practically implemented. The first four directions of research have greater scientific and practical interest in the context of collaboration.

Fig. 4 shows that α^c and α, represented by expressions (1)-(7) with the corresponding right-hand subscripts in relation to the corresponding α, are considered as certain procedures and/or research techniques that are performed on sets of certain components. They make it possible to obtain (symbol → as logical sequence sign) certain results F^c and F, respectively, for the collaborative component (upper right subscript c) and the "traditional" automation component (no upper subscripts).

$$\alpha_1^c : (H \times CIR) \rightarrow \left(F_{\alpha_1}^c = [P,T,V,W,S,...]\right) \quad (1)$$

$$\alpha_2^c : ((H \times CIR) \times IAD) \rightarrow \left(F_{\alpha_2}^c = [P,T,V,W,S,...]\right) \quad (2)$$

$$\alpha_3^c : ((H \times CIR) \times IE) \rightarrow \left(F_{\alpha_3}^c = [P,T,V,W,S,...]\right) \quad (3)$$

$$\alpha_4^c : ((H \times CIR) \times IAD \times IE) \rightarrow \left(F_{\alpha_4}^c = [P,T,V,W,S,...]\right) \quad (4)$$

$$\alpha_5 : (IAD) \rightarrow \left(F_{\alpha_5} = [P,T,V,W,S,...]\right) \quad (5)$$

$$\alpha_6 : (IE) \rightarrow \left(F_{\alpha_5} = [P,T,V,W,S,...]\right) \quad (6)$$

$$\alpha_7 : (\alpha_5 \times \alpha_6) \rightarrow \left(F_{\alpha_7} = [P,T,V,W,S,...]\right) \quad (7)$$

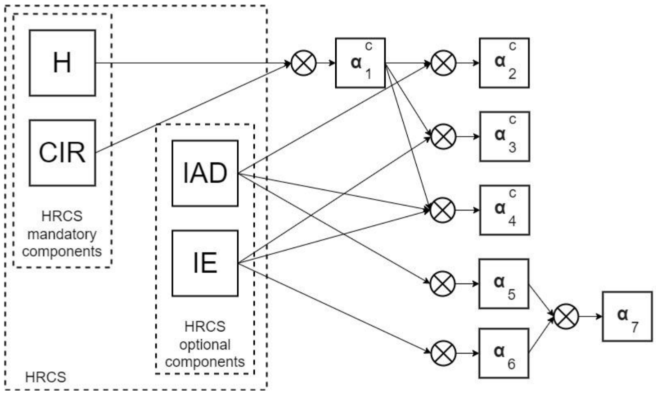

Fig. 4. The structure and relationships of the graph identifying HRCL at sublevel 0-1

Formally, each of the proposed research directions (1)-(7) represents a bijective reflection of the distinguished mandatory and optional components of HRCS on a set of parameters that meaningfully take place during the implementation of the selected executive-hardware-controlling automation components.

For example, for the expression (1) the α_1^c procedure is performed based on the consideration of H and CIR components, which forms (a logical sequence symbol →) the corresponding set of HRCS parameters, namely forces P, moments T, speeds V, power W, safety S (safety) etc. These parameters, for example, for electromechanical drives of robot links, are components of the control level (Fig. 1). They are formed taking into account sensor signals of different physical nature and origin, as well as algorithms, for example, such as algorithms for solving direct and inverse tasks of kinematics and dynamics of manipulation systems of collaborative and conventional IR; algorithms for solving problems of forming collision-free trajectories; secure collaboration algorithms primarily for Human; algorithms for the optimal and/or rational distribution of technological tasks between H and CIR to ensure the given performance of the HRCS, which is determined by speed and reliability; algorithms to ensure the functionality of the HRCS as such; algorithms for implementing specific values of CIR collaboration parameters in case of collision trajectories (probability of collision is obvious), or in case of their prevention, etc.

It should be emphasized that the above mentioned does not contradict the main manifestations of CIR collaboration according to ISO 10218 [16].

In the expressions (1)-(7), the brackets […] mean that one of the parameters in these brackets can be defined, as well as their set in any combination. Many dots indicate the possibility of increasing and introducing new parameters in the process of researching α^c and α. For example, a criterion may be the safety S of the HRCL components functioning, etc.

It is obvious that the above-mentioned α and α^c can be used both when studying the collaborative nature of the above-mentioned CFMS and ordinary FMS, and when studying its individual components. In this case, the latter can be represented by collaborative flexible manufacturing cells (CFMC) or ordinary flexible manufacturing cells (FMC), collaborative or ordinary flexible manufacturing areas, etc.

According to the authors, the obvious directions for further research are the determination of detailing between other levels of the automation pyramid, namely between levels 1-2, 2-3, 3-4. The determination should be based on the system-structural approach. It is interesting to find out the dependencies in the mixierarchic sense, for example, between potentially introduced sublevels 0-1 and 1-2, 0-1 and 2-3, etc. The authors consider the determination of a generalized assessment of the use of collaborative technologies preventive expediency, etc. to be promising. The indicated directions are non-trivial and involve the use of important, first of all, intellectual human resources, as well as the latest technologies for their implementation.

V. Conclusion

A structural analysis of the automation pyramid as a hierarchical structure was performed in the part of levels 0 Field and 1 Control, and an intermediate sub-level 0-1 Human factor was introduced, which reproduces the executive-hardware-controlling component of automation and connections within sub-level 0-1. This made it possible to formally present both the structure of such a sub-level and to formally present scientific research on modern automation and its technological parameters and indicators, taking into account the collaboration factor in CFMS. It was the considered system-structural approach of the interaction of CFMS components that made it possible to formalize the conduct of such studies and determine their content and structure at the executive-apparatus-controlling level.

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