Modular Industrial Equipment in Cyber-Physical Production System: Architecture and Integration

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Abstract—**The design of numerical control systems for industrial machinery is a difficult task, especially when you create universal modular equipment with computer numerical control (CNC). This article presents a modular approach to the design of such systems. The modular control system under consideration is based on a multi-agent network, in which each entity (module) acts as an integral and indivisible part of the object as well as the enlarged structure. This approach allows one to combine the advantages of classical hierarchical control systems with the flexibility and reliability of decentralized multi-agent networks and also to carry out seamless integration of equipment built on the basis of this architecture into a cyber-physical production system (CPPS). The proposed architecture is implemented in the control system of a universal industrial platform. As an example, the apparatus for selective laser curing of a photopolymer to the surfaces of arbitrary shapes is represented. The general structure of the installation determined by the basic hardware and software modules and the network communication protocol are described.**

I. Introduction

Since microprocessors became powerful enough and as their memory capacity increased in the 1980's, the possibility of development from a Numerical Control (NC) to a Computer Numerical Control (CNC) system was obtained. Due to rapid scientific and technological advancement, a great amount of manufacturing equipment was designed and foundational units of CNC system were determined.

Each CNC system consists of three main units: Numerical Control Kernel (NCK), Human-Machine Interface (HMI), and Program Logical Control (PLC). Moreover, the Numerical Control Kernel usually includes an interpreter, an interpolator, an acceleration/deceleration controller, and a position controller, that are literally the main functions. Given the above, various architectures of CNC systems have appeared. However, despite the diversity, all of them were of a closed type. Therefore, changes and additions of new functions or hardware modules were not allowed.

The closed, "monolithic" type of industrial systems architecture is the most common, because it allows minimizing internal errors, eliminating internal unauthorized interference, and also standardizing internal components and control commands. Such equipment is aimed at large enterprises with mass production of products. However, for small companies with a wide range of products, the acquisition and operation of machines with closed architecture is unprofitable. The process of changing the production lines will take a long time, some equipment may be idle or too loaded.

Nevertheless, industrial equipment became a complex set of hardware and software in which providing resource and work coordination, tasks and queries management are necessary things. A CNC system should be flexible, scalable, and interchangeable. Another important fact is an open system architecture that allows you to change the configuration of industrial equipment easily.

Consequently, at the present time the manufacturing community has an increasing desire to gain as much flexibility, agility, and intelligence as possible. These requirements are usually considered at the high level of the *Manufacturing Execution System* [1], [2], where the control of multiple production process elements such as inputs, stuff, machines and support services are enabled. However, the CNC system architecture plays a significant role too. To overcome the closed type architecture problem, this paper introduces a open modular approach to implement an open and flexible architecture.

The proposed approach involves a control system as the consolidation of modules that have their own unique identity but are part of a larger whole. All modules are joined by the multi-agent network, where each module provides an open interface for communication. That is, the system is not just modular but also compatible with the protocol layer. Therefore, the difference between software and hardware modules disappears and makes interconnection easier.

II. Related work

In academia, the multi-agent approach is employed quite actively. Despite the age of the approach, which is rooted from the late 1960's, it is still under development. Researchers have been continually offering various formalization and hybrid architectures.

For example, the combination of web technologies and multi-agent control is described by Ebisa [3]. The system is based on web-services and applied to smart power grids. In addition, another extension of the multi-agent paradigm to smart grids is proposed by Ferreira [4].

Additionally, cloud-based systems are pretty ubiquitous nowadays. However, for manufacturing systems, cloud computing and integration are quite novel. The cloud-based approach poses essential challenges such as security, reliability, availability, etc. Such systems are mostly referred to service-oriented types, but Issa suggested fuzzy design to represent cloud-based intelligent manufacturing [5]. In pursuit of increasing system intelligence, other researchers employ bees algorithms and artificial neural networks to make a agent evolve [6].

Currently, researchers are engaged in various industrial production fields employing agent technologies from production cooperation within collaborative manufacturing to mobile industrial robotics control [7], [8], automated stores management, and stock accountings. Undoubtedly, intelligent manufacturing has many tasks to solve [9], [10]. Supply tasks [11], [12], scheduling tasks [13], [14], job allocation [15], operational control [16], etc. can be solved using the modular multi-agent methodology. Virtually all systems supporting steps of the product lifecycle can be implemented that way.

However, a heterarchical architecture of control is the major multi-agent application field. To overcome CNC challenges a multi-agent CNC controller was developed in Katholieke Universiteit Leuven using an object-oriented paradigm [17]. Also, Lesi V. represents a modularized and decentralized CNC system [18]. The control was released for the conception of modular equipment and met challenges for a plug-n-play automation system. Moreover, a quickly customized and developed CNC system architecture is described by Li S. Z. [19]. As seen above, a huge amount of academic research on intelligent manufacturing has been done including CNC.

The rest of the paper is structured as follows. Section III shows a multi-agent approach to the design of the control system, its mathematical model with regard to domain knowledge features and an example of integration into a CPPS. In Section IV the proposed system is described along with modules such as the driver, vision, laser head, graphical user interface modules, etc. Also, its protocol specification is given in detail. Section V contains the conclusion and future plans concerning system development and improvements.

III. Control system design

A. Multi-agent communication

As a basis for the developed modular control system for CNC equipment, a multi-agent network has been selected. In its essence, any such network is a heterarchical flat structure, that consists of independent entities, called agents. Resources and/or specific tasks are also usually represented by agents. Such an approach allows for the creation of simple and fault-tolerant systems because agents do not require any predefined information about other agents. Consequently, small agent activity deviations can be easily fixed. Global data is forbidden due to agent independence. Therefore, the total performance is highly influenced by agent communication rules.

Obviously, this imposes certain limitations on the performance of the control system, which is unacceptable in solving real-time problems, such as the control of modular industrial equipment. Consequently, various approaches to the implementation of multi-agent networks in the industry were considered [20]. Based on the results of the analysis, the agent-holonic approach was recognized as the most appropriate solution.

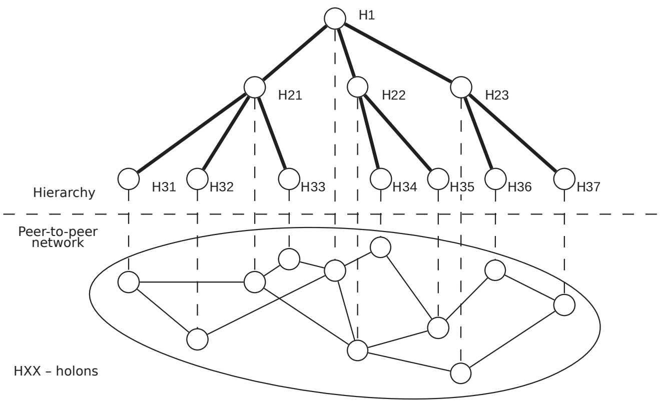

Fig. 1. The general structure of a holonic multi-level system

This approach was first proposed in the 1990's by IMS consortium (Intelligent Manufacturing Systems) [21]. This organization initiated a number of projects aimed the creation of "future manufacturing." One of these projects was Holonic Manufacturing System.

The "holon" term was first used by Arthur Koestler (Kösztler Artúr) to explain biological and social systems evolution [22]. Such systems organize stable transitional forms, that are independent during the whole developing process. However, it is quite difficult to determine where there are wholes and parts in such system organization (Fig. 1).

Hard and soft holons are able to create and modify hierarchical relationships (holarchy) as well as take part in several holarchies at the same time. Even so, holons are absolutely detached as they can receive information from higher order holons and be insensitive to environment perturbations.

Each holon in this distributed network has the ability to be self-monitoring, do a diagnosis, and complete a self-healing function. If an emergency situation occurs, holons complement each other. Every holon possesses the communication interface for information exchange with other holons and holarchy via a bidirectional protocol. Therefore, the current state holon information is available not only for neighbourhood holons but the whole holonic system as well. In addition, each holon has a number of utility functions for different emergency cases. Wherein, a faulty holon can be excluded from the holarchy without any negative consequences.

A distributed holonic system can be based on a holarchy, and consists of autonomous holons (hardware and software modules) with a decentralized control. This architecture of the control system allows for expanding the functionality of the industrial equipment, but can increase fault tolerance, stability, and reliability.

B. Mathematical model

A mathematical model of the holonic control system is determined by a unified abstract representation of the multi-agent environment (MAE), allowing it to further proceed to the holonic structures. Unification is achieved through a uniform definition, which allows on the basis of data about the agent (holon) the ability to draw conclusions about the state of its environment and vice versa [23].

This approach, in turn, makes it possible to build an isomorphic MAE on the basis of a given MAE, where a group of agents can be combined to create a single holonic agent (holonic synthesis) and a single agent can be divided into the group of the holonic agents (holonic decomposition) [24].

The holonic multi-agent environment of the represented control system can be represented as a tuple (1):

$$\mathfrak{hE} \stackrel{\text{def}}{=} \left\langle \mathfrak{A}, \mathfrak{E}, \mathfrak{P}, \mathfrak{Fe} \right\rangle, \tag{1}$$

where $\mathfrak{A} = \{\mathcal{A}_{\mathcal{g}1}, \ldots, \mathcal{A}_{\mathcal{g}n}\}$ is a set of the agents. Each agent is a tuple (2):

$$\mathcal{A}_{\mathcal{g}i} = \langle \mathcal{S}_i, \mathcal{P}_i, \mathcal{A}_i, \mathcal{F}_i \rangle, \tag{2}$$

where $\mathcal{S}_i$ is a set of the agents' states, $\mathcal{P}_i$ is a set of the perceptions of the agents, $\mathcal{A}_i$ is a set of the actions of the agents, $\mathcal{F}_i$ is the agent function (3):

$$\mathcal{F}_i \colon \mathcal{S}_i \times \mathcal{P}_i \to \mathcal{S}_i \times \mathcal{A}_i \,. \tag{3}$$

$\mathfrak{E}$ is a set of the environment's states, $\mathfrak{E} = \{\varepsilon_1, \ldots, \varepsilon_n\}$. $\mathfrak{P} \colon \mathfrak{E} \to \big(\mathcal{P}_1 \times \ldots \times \mathcal{P}_n\big)$ is a perception function, $\mathfrak{Fe} \colon \mathfrak{E} \times \big(\mathcal{A}_1 \times \ldots \times \mathcal{A}_n\big) \to \mathfrak{E}$ is a environment function.

It is assumed that there is a discrete time scale, where the time step is given by the transition from one time point to another time point. Each agent $\mathcal{A}_{\mathcal{g}i}$ for all states of the environment $\varepsilon \in \mathfrak{E}$ and all states of agents (4):

$$(\mathcal{s}_1, \ldots, \mathcal{s}_n) \in \mathcal{S}_1 \times \ldots \times \mathcal{S}_n \tag{4}$$

at each step of computation gets its local object of perception $\mathfrak{P}^i(\varepsilon)$ through the perception function. Agent calculates its new action (5) based on its current state $\mathcal{s}_i$, and its own perception of this state.

$$\mathcal{A}_i = \mathfrak{F}_i^1(\mathcal{s}_i, \mathfrak{P}^i(\varepsilon)), i \in \overline{1, n} \tag{5}$$

In the other words, a state of the environment is changing under the influence of agents. Equation (6) defines a successive state of the environment, and (7) defines a successive state of the all agents i in the environment.

$$\varepsilon' = (\varepsilon, \mathcal{A}_1, \ldots, \mathcal{A}_n) \tag{6}$$

$$\mathcal{s}_i' = \mathfrak{F}_i^2(\mathcal{s}_i, \mathfrak{P}^i(\varepsilon)), i \in \overline{1, n} \tag{7}$$

The transition state function (8):

$$\widehat{\mathfrak{Fe}} \colon \mathfrak{E} \times \mathcal{S}_1 \times \ldots \times \mathcal{S}_n \to \mathfrak{E} \times \mathcal{S}_1 \times \ldots \times \mathcal{S}_n \tag{8}$$

defined as follows (9):

$$\widehat{\mathfrak{Fe}}(\varepsilon, \mathcal{s}_1, \ldots, \mathcal{s}_n) = (\varepsilon', \mathcal{s}_1', \ldots, \mathcal{s}_n'), \tag{9}$$

combines the agents' states and environment's states. Consequently, the perception function, the agent function, and the environment function are part of the transition state function $\widehat{\mathfrak{Fe}}$.

Based on the previous explanations, it is clear that any holon of the considered control system should take its own object of perception, calculate action and next state from previous state without the reference to the other holons' states with any environment state.

Two multi-agent environments (10) and (11):

$$\mathfrak{hE} = \left\langle \mathfrak{A}, \mathfrak{E}, \mathfrak{P}, \mathfrak{Fe} \right\rangle \tag{10}$$

$$\mathfrak{hE}' = \left\langle \mathfrak{A}', \mathfrak{E}', \mathfrak{P}', \mathfrak{Fe}' \right\rangle \tag{11}$$

are isomorphic if there exists a bijective function (12):

$$\mathfrak{B} \colon \mathfrak{E} \times \mathcal{S}_1 \times \ldots \times \mathcal{S}_n \to \mathfrak{E}' \times \mathcal{S}_1' \times \ldots \times \mathcal{S}_n' \tag{12}$$

such that, for all states in the environment (13):

$$(\varepsilon, \mathcal{s}_1, \ldots, \mathcal{s}_n) \in \mathfrak{E} \times \mathcal{S}_1 \times \ldots \times \mathcal{S}_n \,, \tag{13}$$

we have the equality (14):

$$\widehat{\mathfrak{Fe}}'(\mathfrak{B}(\varepsilon, \mathcal{s}_1, \ldots, \mathcal{s}_n)) = \mathfrak{B}(\widehat{\mathfrak{Fe}}(\varepsilon, \mathcal{s}_1, \ldots, \mathcal{s}_n)) \tag{14}$$

In connection with this, attention is drawn to the fact that every MAE has two special configurations. The first is the environment without the agents, in which all state changes are defined by an environment function $\mathfrak{Fe}$. The second is the MAE with only one permanent state and only one agent, where all states of this agent defined by agent function $\mathfrak{B}$.

This formalization enables us to reduce the MAE, which includes a several agents, to the environment with the only one agent. Concurrently, all the other agents are represented as the subject of this environment.

If (15) is multi-agent environment,

$$\mathfrak{hE}^\dagger = \langle \{\mathcal{A}_{\mathcal{g}1}, \ldots, \mathcal{A}_{\mathcal{g}n}\}, \mathfrak{E}, \mathfrak{P}, \mathfrak{Fe} \rangle \tag{15}$$

then for each $i \leq n$, there exists an isomorphic multi-agent environment. Without loss of generality, let $i = 1$. Let us create an environment (16):

$$\mathfrak{hE}^\dagger = \langle \{\mathcal{A}_{\mathcal{g}i}\}, \mathfrak{E}, \mathfrak{P}, \mathfrak{Fe} \rangle \tag{16}$$

such that $\mathfrak{E}' = \mathfrak{E} \times \mathcal{S}_2 \times \ldots \times \mathcal{S}_n$, $\mathfrak{P}' = \mathfrak{P}^1$, for all $(\varepsilon, \mathcal{s}_2, \ldots, \mathcal{s}_n) \in \mathfrak{E}'$ and $\mathcal{A}_1 \in \mathcal{A}_1$ environment function (17):

$$\mathfrak{Fe}' \colon \mathfrak{E}' \times \mathcal{A}_1 \to \mathfrak{E}' \tag{17}$$

defined as follows (18):

$$\mathfrak{Fe}'((\varepsilon, \mathcal{s}_2, \ldots, \mathcal{s}_n), \mathcal{A}_1) = (\varepsilon', \mathcal{s}_2', \ldots, \mathcal{s}_n'), \tag{18}$$

where (19):

$$\varepsilon' = \mathfrak{Fe}(\varepsilon, \mathcal{A}_1, \mathfrak{F}_2^1(\mathcal{s}_2, \mathfrak{F}^2(\varepsilon)), \ldots, \mathfrak{F}_n^1(\mathcal{s}_n, \mathfrak{F}^n(\varepsilon))) \tag{19}$$

is a successive state ε in the $\mathfrak{hE}^\dagger$ for $\mathcal{A}_1$ and the other actions of agents.

Equation (7) defines a successive state $\mathcal{s}_i$ of the all agents i in the $\mathfrak{hE}^\dagger$ for $2 \leq i \leq n$, which implies the existence of an isomorphism between two MAE, and we can begin to identify the concepts of "holonic synthesis" and "holonic decomposition."

Hence, on the basis of the above equations, we can conclude that it is possible to combine several agents into one holon and vice versa. Thus, we can dynamically change the structure of the designed computer numerical control system.

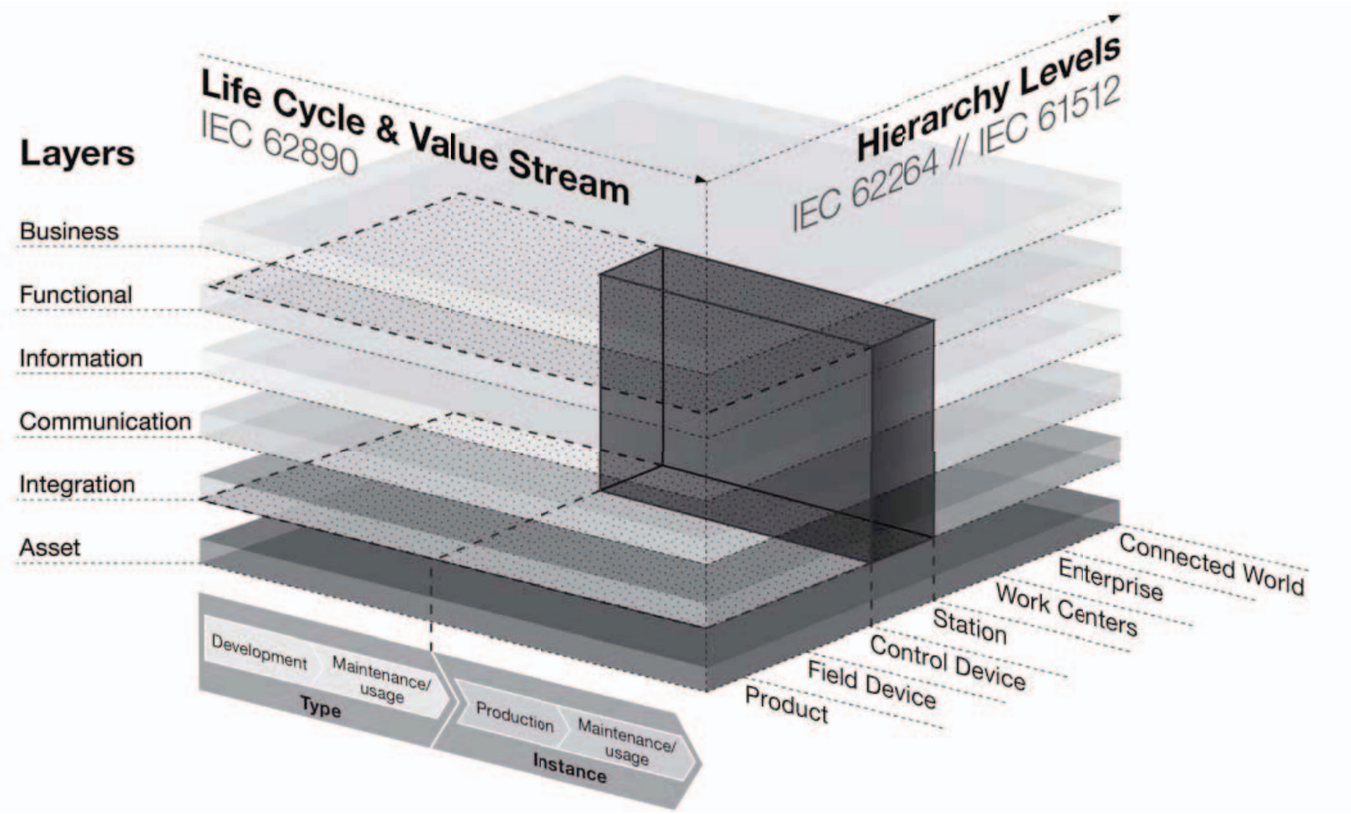

Fig. 2. Mapping the proposed architecture on the RAMI 4.0 reference model

C. CPPS integration

The developed mathematical model in itself allows creating a control system for modular industrial equipment. This system will have the flexibility of multi-agent networks and the stability of hierarchical management structures. However, this is not enough to argue that industrial equipment built on the basis of this control system can become a part of the cyber-physical production system. The fact of the matter is that for today there are some standards of representation of industrial cyber-physical systems. From the diversity of standards associated with the concepts of industrial cyber-physical systems and Industry 4.0, two most well-known ones can be distinguished. This is *Reference Architectural Model Industrie 4.0 (RAMI 4.0)* [25] and *Industrial Internet Reference Architecture (IIRA)* [26]. From these two options, the RAMI 4.0 model was chosen. The main prerequisite of this decision was the greater compliance of this reference architecture with Russian production standards, due to the fact that the IIRA is more oriented to the industry of the United States of America, and RAMI 4.0—European Union.

The RAMI 4.0 model is hierarchical and three-dimensional, and in three axes it displays the subject area in terms of information technology, product life cycle and production organization.

On the axis “Hierarchy Levels”, modular industrial equipment is located at the levels of “Station” and “Control Device” because such equipment used in repetitive or discrete production. It is also obvious that such equipment is not included in the “Field Device” area, since it has no connection with them directly. The axis of the “Value Stream” is of the greatest interest, since this axis is directly related to IT, which means that it represents a control system for modular technological equipment. Thus, the multi-agent control system considered earlier is located at the levels “Integration”, “Communication”, “Information” and “Functional” (Fig.2).

At the level of “Integration”, modular equipment interacts with the “real world”, that is, with the operator through the HMI. At the level of “Communication”, it communicate with the internal modules and other equipment to solve problems in real time. At the level of “Information”, it provides compatible data representation and access for all components of the CPPS. At the functional level, the modular equipment control system describes its capabilities as services for other components of the CPPS, which is the basis for describing the business process (the next level).

From all of the above, it can be concluded that the modular equipment can be projected onto the reference model RAMI 4.0. In this case, the control system architecture corresponds to the hierarchy of levels of the given model. Modular industrial equipment can become a component of the CPPS.

IV. APPLICATION EXAMPLE

The proposed control system is used in the universal industrial platform. As an example, let us consider the implementation of one of the types of equipment constructed on the basis of this platform. This is an apparatus for selective

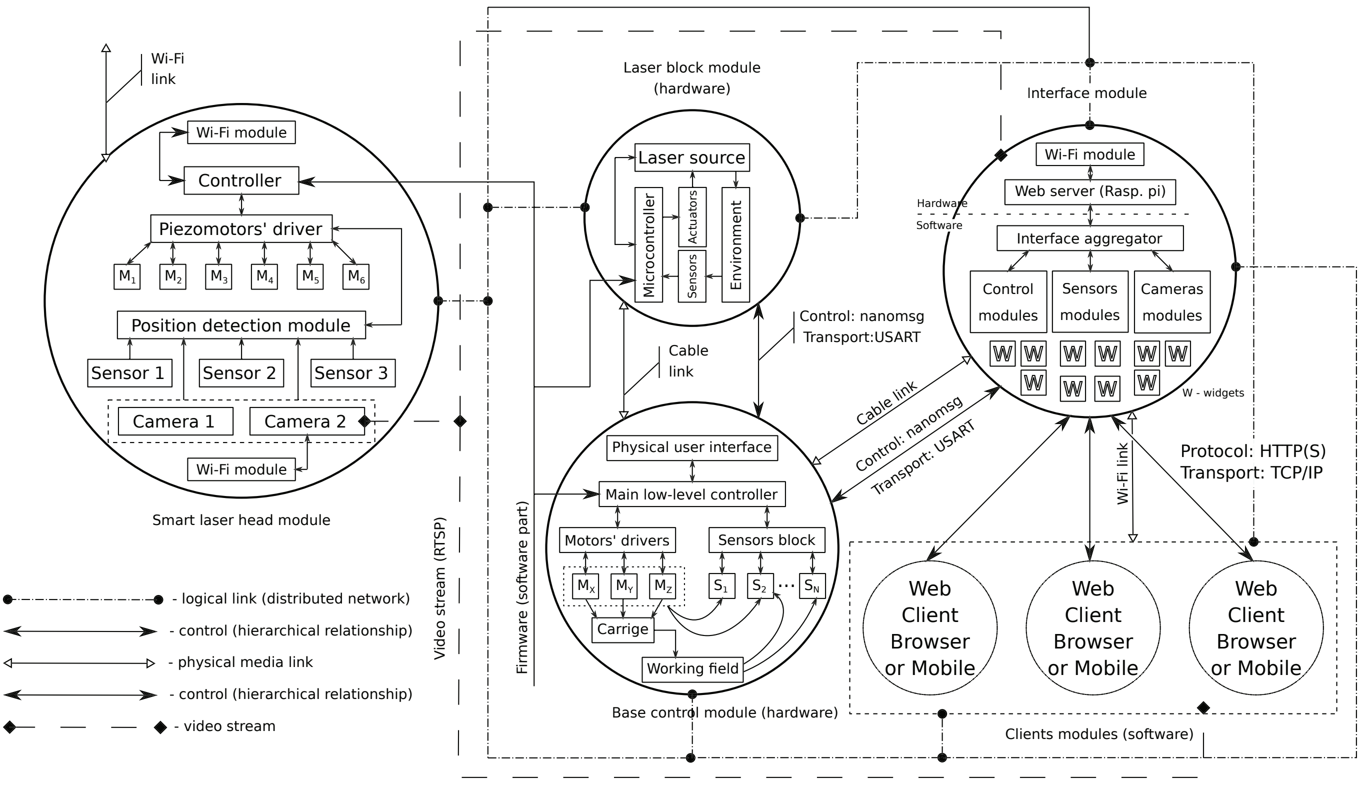

Fig. 3. The architecture of the modular equipment

laser curing of the photopolymer to the surfaces of arbitrary shape [27–31].

This equipment uses laser processing technology the same as the LDF (Laser Direct Structuring) process. The experimental testbed represents a device for arbitrary surfaces processing by laser emition. The equipment contains a fixed coordinate table where processing the object takes place, a laser head is placed over the work table and is movable in a horizontal plane along two coordinates with a laser emitting source (laser module) connected optically with the laser head. Structure of its modules and their interaction with each other are described in more detail in previous paper [32].

The laser head has a gyro-stabilized suspension system based on the modified Stewart platform. Linear piezo motors are used for platform moving. The suspension system allows the laser beam deflection on two self-perpendicular surfaces and focus distance changing by the head objective moving along Z-coordinate.

Every module of this apparatus is a close independent entity, highly specialized and solved only one of a few tasks, determined in the system, such as query processing, data providing or CNC program generating. Entities can interact on the unified protocol level and, as already reported above, software, hardware, and mixed parts are similar from the system's point of view. The proposed system uses an open protocol which allows adding new modules "on the fly." It is a necessary property for making system design easier and for providing an interchangeability of modules. The system examined below uses holonic units for blocks' presentation which contains a set of holons interacting inside their unit.

Platform components are represented as a set of small simple parts joined in a big device with a few functions, which interact with neighbours by data transitions. At this point each part must have a clear understanding of its own task regardless of what role it has: master or slave. The architecture of the modular equipment is depicted in Fig. 3, 3D-model of the apparatus in Fig. 4. Equipment can contain many types of modules that are classified into three main groups by functions.

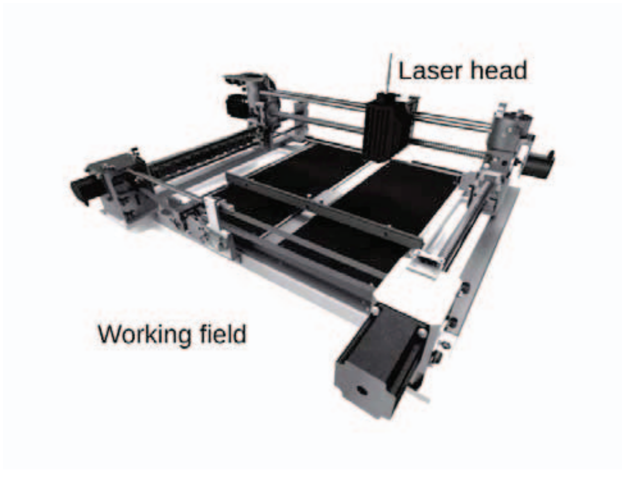

Fig. 4. Experimental apparatus

The interface module provides a link between users and equipment. The user connects to the server by the web-application and sends a request to the device with CAD-file or CNC-program; the CNC-program should be checked for accuracy. Furthermore, the application monitors the operation process and sends notifications to the user about important events. This unit is mainly software.

The base control module has the master role and contains the CNC-module and a set of drivers and sensors for the control of physical devices. CNC-program processing, sending current status signals to the server and device's display, and making decisions about the current situation are its main tasks. This unit is mainly hardware.

The smart laser head module is a slave for the controls unit and associates software and hardware modules. Basic types of holons:

- main camera, which runs availability and the size of blank detecting, reference point labels searching and watching the processing operations;
- the machine vision component with special frame processing algorithms;
- a laser module with surface incline detection camera;
- a set of sensors for self-diagnostics and modules work.

The link channel between units is based on NanoMsg, the socket library for a message exchange by network elements. The NanoMsg acts at the top of a transport layer, provides several types of communication, works at a high speed and is easy to scale. The library is open source project and it makes the system non-proprietary; a unified message standard allows for expanding the system while including new modules in it. The protocol acts between all modules except the client-server link, which uses HTTP-protocol.

V. Conclusion

In this work, advantages of the modular agent-holonic approach to the organization of industrial control system with numerical control was considered. A review of the literature on this topic was conducted. The main advantage of the approach is the equivalence of the components from the point of view of the system, which allows one to adapt the system to changing production conditions, which corresponds the principles of cyber-physical production. The correspondence of the Reference Architectural Model Industrie 4.0 (RAMI 4.0) is also shown. The system is based on the proposed peer distributed network of nodes and each of them performs its function in the system. A mathematical study was carried out to analyse the control system as a whole, and the behaviour of its components. The developed mathematical model describes the dependence of the behaviour of the agents represented the modules of the system on the states of the external environment. Also, this model shows the ability of modules to the composition and decomposition.

The description of the system components was given. According to it, the system has a number of basic blocks that perform a common function: the control unit, the client-server part and the smart unit that performs the support processing function. NanoMsg has been chosen as the basic communication protocol. It allows to make a one-tier system, and it will be open to the introduction of new components. The approach involves almost the complete autonomy of the components, which simplifies scaling and improves fault tolerance.

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