Protocol for Organization of a Decentralized Autonomous Agents Network in Factories Using Market Mechanisms

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***Abstract*—The paper describes work organization methods for factories with plenty of autonomous agents with the help of market mechanisms what authors call robot economics. As a technological basis, the application of decentralized technologies is presented and justified: Blockchain technologies and smart contracts of the Ethereum network. The work is an extension of the article "Blockchain-based protocol of autonomous business activity for multi-agent systems of UAVs" and describes in more detail the architecture of the robots economics protocol. The main attention is paid to the protocol functionality and its basic elements. There is a description of the architecture of an autonomous agent working on the principles of robot economics in the article. The article shows how the work of agents is organized and how the self-correction of the factory and its agents happen. As a result, the experience of approbation of the presented methods in experiments is presented.**

***Index Terms*—cyber-physical systems, autonomous agents, multi-agent system, distributed systems, Blockchain**

I. Introduction

Global change of most production processes is expected in the near future [1] due to the significant potential of robotic systems. They are able to adapt [2] to a wide range of tasks, they are more effective in many types of operating activities, and they reduce time expenditures for production. Robotization of production is growing: the world average number of robotic units per 10,000 employees of enterprises increased by 11% from 2015 to 2016 [3]. For example, only in Central and Eastern Europe in 2017 they were equipped by 28% [4] of robotic units more than in 2016. Most entrepreneurs see in robotics the possibility of increasing the efficiency of their production and compensating for the shortage of personnel [4].

It is necessary to clarify exactly how the massive introduction of robotic systems is predicted. Systems of computing devices that, on the one hand, cooperate with one another through network services for access and data processing, and on the other hand actively interact with the surrounding physical world, appear to be the concept of cyber-physical systems (CPS) [5]. The main technological trends of this concept, in addition to autonomous robots, are Big Data, Internet of Things, cloud computing, etc. Cyber-physical systems are a concept key element of Industry 4.0 [6] — the fourth industrial revolution, which is due to the introduction of CPS. The scale of the changes is predicted to be so significant that they will affect and change [7] not only production methods, but also the fundamental principles by which humankind was engaged in industry.

Thus, these global changes pose a lot of new challenges to scientists and developers. One of the important issues [8] that is in the way of autonomous agents introduction (we combine robotic systems, smart things and software agents into this concept) into production and which is considered [9] by researchers in robotics field is the issue of organizing a joint and well-functioning work of a multitude of agents [10]. Moreover, the specific features [11] of the modern industry resulted in the fact that the centralized structure of organizations has faced great costs associated with the risks of failure,

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errors or hacking [12]. Researchers believe that distributed approach to production is getting more practical: owing to it, transaction costs [13] (costs for contracting), transportation costs, storage costs and equipment obsolescence costs are reduced [14]. Because of this, decentralized systems are the most promising in production [15].

Let's denote the key moments of the problem of arranging the work of set of agents taking into account applicability in industry:

- Flexibility of work [8] — the organized work of agents should adapt to the rapidly changing requirements of production;
- Scalability [8] — the system of autonomous agents should be easily extensible;
- High quality feedback [8] — measuring quality, productivity and profitability of production requires accurate data on the work of agents in a convenient form;
- Fault tolerance [8] — a multiagent system should be as robust as possible to the faults of individual agents and to failures in the very principle of interaction, especially at highly dangerous enterprises;
- Security [16] — in a large, expensive and secret production the system should show resilience to hacking attempts by intruders.

There are thus architectural issues of organizing the work of autonomous agents:

- Organization of agent's intelligent behavior [8];
- Standardized method of cooperation, coordination and joint decision-making between agents [17].

The most vivid and full use of autonomous agents in production was embodied in the idea of smart factories. Smart factories [18] are the factories in which autonomous production takes place through the collection, exchange and use of information between people, materials and machine systems using modern network technologies. In machine systems, not only autonomous robots are combined, but also separate equipment, intelligent control systems and various software modules. In its final version, smart factories are engaged in release of products without human participation, automatically adjusting their production process, if necessary.

In such a large-scale structure, the problems of organizing the joint work of agents become critical, and the level of responsibility of the technology used for organizing work increases significantly. First of all, the protocol of interaction [19] goes through it because of a significant number of heterogeneous devices and programs involved in production (for example, interaction of a manipulator and an aircraft that are engaged in loading and delivery of cargo). Secondly, the critical factor is fault tolerance and cybersecurity [20] of a smart factory. Thus, there is already a request for a safe and efficient way to organize the work of autonomous agents.

Today many researchers are engaged in this task both for ordinary enterprises and for future smart factories. In paper [21], the authors offer their cyber-physical architecture for enterprises explaining how the joint work of cyber-physical systems will be organized. Article [22] describes a network protocol of interaction for a number of devices of industrial Internet of Things. The authors of article [23] are developing their own framework for coordinating autonomous agents at a smart factory.

In paper [24], the authors study the applicability of decentralized technologies for Internet of Things proving the advantages of these technologies for creating secure communications between agents.

In this article, we present our methods of organizing the work of autonomous agents at enterprises based on market mechanisms. We speak about their basic principle in section 2. The technological basis of the project is given in section 3 and the description of its architecture is given in section 4. The process of interaction between agents is described in section 5. In section 6 we show a general description of the work of a smart factory using the presented methods. Section 7 gives examples of the implementation of the developed system in reality.

The work expands the topic of organizing the work of autonomous agents with the help of decentralized technologies raised in the article "Blockchain-based protocol of autonomous business activity for multi-agent systems of UAVs" [25]. This paper differs from the mentioned one with the analysis of market mechanisms as the principle of organizing the work of agents as well as a more detailed architecture of the protocol of economic interaction. In addition, this work is concentrated on autonomous agents in general and on their work as part of a smart factory in particular, in contrast to the organization of the interaction environment for unmanned aerial vehicles in the previous article.

II. Robot Economics as a Principle of Organizing a Multi-agent System

So, the main question which developers of the work organization system of autonomous agents should answer is what should be the basic principle by which agents choose their own behavior and agree with one another. As noted above, the principle should take into account decentralized nature, multiplicity and heterogeneity of autonomous agents system.

As for today, there are examples of a functioning structure of limited automatic behavior of multiple agents. These are automated trading systems [26] or "trading robots" — software agents designed to automate financial transactions. In addition to facilitating routine work for traders, these systems using market mechanisms embedded in their algorithmic strategy, participate in the organized work of markets and exchanges. Often the goal set before a "trading robot" is profit maximization, which allows quantifying the effectiveness of its work. Moreover, modern researchers are already considering the organization of business processes [27] with the help of autonomous agents systems.

Thus, both economic and manufacturing spheres expect significant participation of autonomous agents, which establish commodity-money relations. For example, inside smart factories some agents will resolve economic issues, and then regulate the activities of other agents that form the production process.

We affirm that the market mechanism of organization is applicable to the work of autonomous agents system. Indeed, such an approach was already used in the past. For instance, successfully implemented methods for coordinating a multi-agent robotic system based on a market mechanism are analyzed in paper [28]. The authors give a market decision-making strategy for tasks distribution between autonomous vehicles in paper [29]. Similar problem of assigning tasks to a lot of robots is solved by the authors in article [30]. Cost functions are used to plan the execution of tasks by agents in publication [31]. Competition and cooperation between them arise when robots try to maximize their personal benefits expressed by internal cash. In article [32], authors consider a similar market mechanism for cooperation but with the addition of agent-leaders who can optimize the actions of robot subgroups collecting information on the status of work execution so that the task is performed in a more profitable way. A similar system is used in work [33] to organize reliable collecting information by agents minimizing costs. Most of such articles are focused on describing and demonstrating the most marketable principle of coordinating agents proving its efficiency. Unfortunately, these studies practically do not address all other issues related to the organization of multi-agent system, especially safety issues, and the application of results is limited to laboratory studies.

It is necessary to explain why the market mechanism is effective for organizing multi-agent system work. At present, many economists advocate a new institutional economic theory [34], in which the absolute effectiveness of market mechanisms is disputed. In particular, the economist R. Coase in his work "The Nature of the Firm" [35] emphasizes that over the years initially effective mechanism of prices as a way of communication is forced out of economic structure and replaced with centralized coordination of entrepreneur. However, while the number of elements subordinate to coordinator increase, the costs for their coordination (transaction costs) also increase. They include [36] the costs of collecting and processing information, making decisions on contracting and monitoring implementation.

Thus, we obtain efficiency criteria of market mechanisms, depending on the costs of coordinating a multitude of agents. Thanks to it, we can find out how many autonomous agents can be in a system of market mechanisms, so that it remains effective. What is more, with a decrease in transaction costs, efficiency will increase [37].

Previously, it was said that decentralized systems have lower transaction costs than centralized ones: in decentralized systems, an environment can be created where the cost of contracting and monitoring contract performance is significantly reduced [38].

It becomes clear why despite a sufficient number of studies systems of economically interacting agents were not used in real technological processes. The main obstacle to their full implementation in production was the lack of methods for creating a communication environment with low costs, in which the objects of the physical world, autonomous agents and their program logic would be uniquely linked. The organized and safe work of smart factories requires adequate execution of agent algorithms affecting physical objects to be ensured. However, the emergence of developed network and new decentralized technologies in recent years makes it possible to ensure the existence of such an environment.

Relying on the works of economists and researchers of multi-agent systems, we propose to use a network of autonomous agents for organizing smart factories work functioning according to the principles of market mechanisms. The behavior and communication of participants of such a network is regulated by the circulation of currency or its analogue and the desire to increase its capital. When concluding a contract between agents, the subject of the agreement is behavior program logic, and its terms of fulfillment are developed in the process of supply and demand.

We call the described method of organizing robot economics or robonomics. It's the organization of a network of cyber-physical systems based on economic relationships. The main elements within this network are program lists of proposed or accepted tasks for a certain cost. These lists we unite in the concept of liability markets of cyber-physical systems. The principle of robonomics is equally applicable both at the micro level of the workshop of a smart factory, where agents perform work for the internal analogue of money resources, and at the macro level of the set of functioning factories that sell their products for real capital.

The question of the technological basis of robot economics will be discussed in the next section.

III. Decentralized Technologies

The question of creating an environment for organizing the work of robonomics network, as we have already found out, is very important. To this end, we use modern peer-to-peer technologies that combine [39] the technical and economic nuances of robonomics infrastructure.

A. Blockchain

As a technical basis for interaction between agents, we used Blockchain technology. It allows creating a peer-to-peer decentralized network for multiple agents [40] with an information protection mechanism what covers the need for security for smart factories [40]. An important principle of Blockchain, which makes it compatible with market mechanisms, is the mechanism of transactions [41]. Participants in decentralized network send data on arrangements to a distributed network, and then special nodes according to certain rules for their confirmation validate the data.

The special feature of the technology is that it prevents the data from being changed in transactions, but at the same time preserves the publicity of the relations between the nodes in the network. The network of autonomous agents will be protected [24] from incorrect changes caused by a faulty data source, a separate agent or external intruder, and will be transparent to monitoring.

Of course, the developing technologies of Blockchain have disadvantages. Part of the technical questions to the technology centers around the very principle of network consistency. For example, there may be situations when the entire network is divided into two different branches due to the actions of the participants, which leads to a change / loss of data in transactions or a change in the transaction confirmation rule. This phenomenon has been called soft and hard forks [42]. However, the full use of this shortcoming to compromise the network requires significant computing power. Another problem of Blockchain is its size and capacity [42], what can be critical for robotic systems in production. This problem is being solved: it is proposed to introduce new compression algorithms and use partial data queries in Blockchain.

B. *Smart Contracts of Ethereum Network*

For a while Blockchain was a technology focused only on the circulation of transactions of virtual money, crypto currency. However, in 2013 V. Buterin proposed Ethereum protocol [43], which first realized the idea of wrapping software logic in a secure transaction to ensure its implementation. It's called smart contract [44]. The very principle of smart contracts was proposed at the end of the 20th century by the cryptographer N. Sabo [45], but there was no environment that would guarantee the performance of the contract and access to the objects indicated in it. For the first time, Ethereum protocol made it possible to conclude contracts between agents for the execution of program logic being Turing complete [46].

C. *Applicability of Smart Contracts for Smart Factories*

The principle of smart contracts as a technological basis is well suited for the implementation of a multi-agent robotics system. For example, the same V. Buterin in his publication [47] describes the mechanism for predicting market changes with the help of contracts to assess its future volume.

Nevertheless, the traditional approach to creating a decentralized market by means of smart contracts has a problem: it has the problem of scalability [48] critical for creating smart factories. Any information about a contract received during its execution will be sent to Blockchain in the form of a separate transaction, what leads to an expensive use of such a system.

To solve this problem, we propose to remove from smart contract the logic connected with the relevant information on contract performance. To do this, we introduced an additional peer-to-peer network, which provides information exchange in the form of a distributed file system. An example of such a system is IPFS (InterPlanetary File System) [49]. It's a content-addressable peer-to-peer communication protocol. Only after the final agreement between the agents and the corresponding transaction in Blockchain, they will exchange basic information about the contract through this network, sending each other network file identifiers.

IV. Robonomics Architecture

Having taken the methods and technologies of robonomics described above as a basis, in 2015 we began to develop the project AIRA (Autonomous Intelligent Robot Agent) [50]. It's a platform for creating organized work of cyber-physical systems. This is what we propose to use for creating smart factories. The key points of the architecture of our platform are given below.

A. *Communication between Agents*

As mentioned earlier, cooperation between agents occurs through the conclusion of transactions in Blockchain and the exchange of information via IPFS protocol. For convenient organization of mass dispatch of requests for supply and demand, which have general features (for example, messages on cargo transfer performance), they are allocated to separate isolated channels, topics. Each agent can act as a publisher of messages to a topic and a subscriber to a topic to listen to available queries. Having found the r target request or having received a response to its, the agent proceeds to the design of a smart contract and further actions. Thus, a topic acts as a liability market, where agents make transactions. Messages are recorded in Base64 encoding using JSON (JavaScript Object Notation) data exchange format [51].

B. *Tokens*

To use market mechanisms for organizing the work of agents, an internal analogue of money resources is necessary. By means of it, transactions will be concluded and the quantitative evaluation of work will be measured. Blockchain technology allows the use of crypto currency mechanism for these purposes: it is possible to issue your own crypto currency or use existing ones. A unit of a crypto currency or a token [52] is a certain unit of digital money balance, which is the same record in Blockchain using transactions.

V. Autonomous Agent Design

A. *Communication Standardization*

Because of the existence of a huge number of robotic systems, which have different sets of software, libraries and frameworks, organizing their collaboration is difficult. The solution to this problem consists of using an open communication standard for cyber-physical systems.

Such a standard was proposed during the development of the project Robot Operating System (ROS) [53]. ROS is a hight-level industrial framework that provides publisher / subscriber communication method described above and the formalization of communication data.

The infrastructure of robonomics links smart contracts Ethereum and any cyber-physical systems [54] compatible with ROS. For this purpose, an application for ROS was implemented, aira_ros_bridge, which performs a low-level connection of an agent with a smart contract. Together with it, a unified contract for processing a transaction between autonomous agents, RobotLiability, operates.

B. Agent Architecture

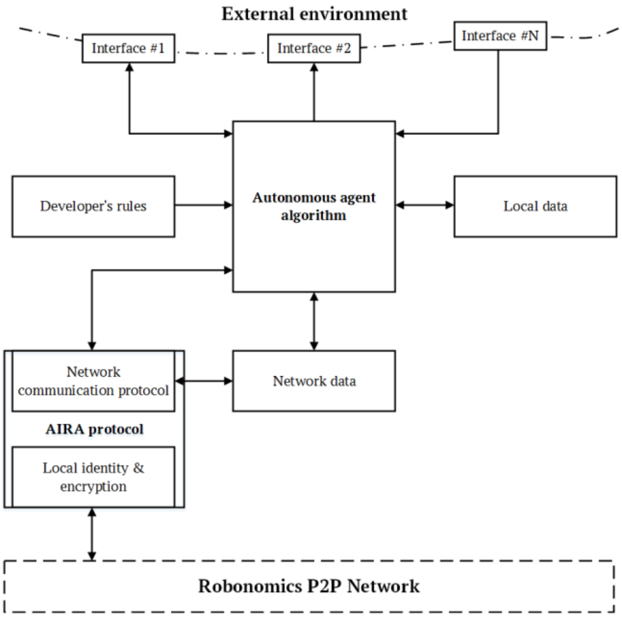

Figure 1. Autonomous agent architecture: the dashed line shows decentralized network, the direction of the arrows indicates the possibility of one-way or two-way data transmission.

The actions of an autonomous agent are regulated by its software logic: economic algorithms determine optimal behavior strategies, interaction with the environment is performed by means of interfaces (manipulator interface, engine interface, etc.), and communication with the network is organized by the above described communication methods performed in the network communication protocol.

Let's consider the general scheme of autonomous agent architecture, presented in Fig. 1. The internal mechanism of the agent is organized using Robot Operating System. The data used by the agent are represented by two blocks: the agent stores its own local work data not associated with robonomics network and has network data protected by Blockchain mechanism. It is important to note that, unlike local data, network data are required for the agent to function on the network.

Also the scheme shows the blocks of interfaces for agent environment and the rule block of the agent developer where the developer instructions are written. In general, the agent does not have to have a block of rules or interfaces to the outside world (for example, if an agent is a lighthouse or validator node, then all its work is concentrated in the network).

The connection with robonomics infrastructure and the necessary software are recorded in AIRA protocol block. It contains several modules responsible primarily for network interaction as well as related work mechanisms of agents within robot economics.

The network communication protocol communicates directly with the network data, and the agent provides the local data to it. In addition, the protocol is responsible for identifying the agent in robonomics network.

VI. Smart Factory Operation

Let's consider the process of smart factory work via an example. Fig. 2 shows the operation scheme of a running smart factory that collects useful data by a large number of agents with sensors.

The work of agents at the lowest level is organized by robonomics methods. The results of their work are accumulated by a large node Automatic data collection system. Agents supply their data to it. This is how the information on technological process of the factory is collected.

Then the data gets into robonomics network with the help of AIRA protocol. The workflow is stored in IPFS file system, and its cryptographic identifier is published by means of smart contract in Blockchain.

After this, the organization of the proposal for potential customers begins. To do this, you need to create a decentralized application (DApp). This is an application software for user interaction with decentralized networks. One such application is Sensory Data Analysis service. It analyzes collected data, forms an offer for a client and sends it to the customer support service (for example, online store website). Now any customer or even DApp of another organization can buy this data.

Let's consider the process of demand. A client contacts the support service with a request to perform a specific work. The request is transferred to the decentralized network by Smart Factory Orders service application. The application draws up the necessary smart contract and loads the parameters of the new workflow into IPFS file system. After registration of the liability, the smart factory begins its execution downloading the parameters of the liability from IPFS and reproducing them locally. Proposals for data collection are sent to the agents.

VII. Experiments in Organizing Robots Economy

Starting from 2015, we are engaged in approbation of the developed methods in various projects. To present the capabilities of our platform, we simulated [55] the work of several smart factories that react to changing capital at the markets of four types of different goods.

Then a laboratory stand was assembled [56] simulating the production and economic process.

The stand works as follows. First, a consumer market simulation, which forms a demand for the goods of factories, is launched. Smart factories and their warehouses select the markets they need, thereby forming offer. The infrastructure of robonomics finds a correspondence between supply and demand, and then smart contracts for factories and warehouses are created. This starts the process of supplying raw materials to the factory. As soon as the work of the factory is over, the finished product is sent to the warehouse and is waiting for purchase.

The user does not know all the information about consumer demand and is free to make a prediction about which of the markets will be highly-demanded. To do this, he places capital at the markets.

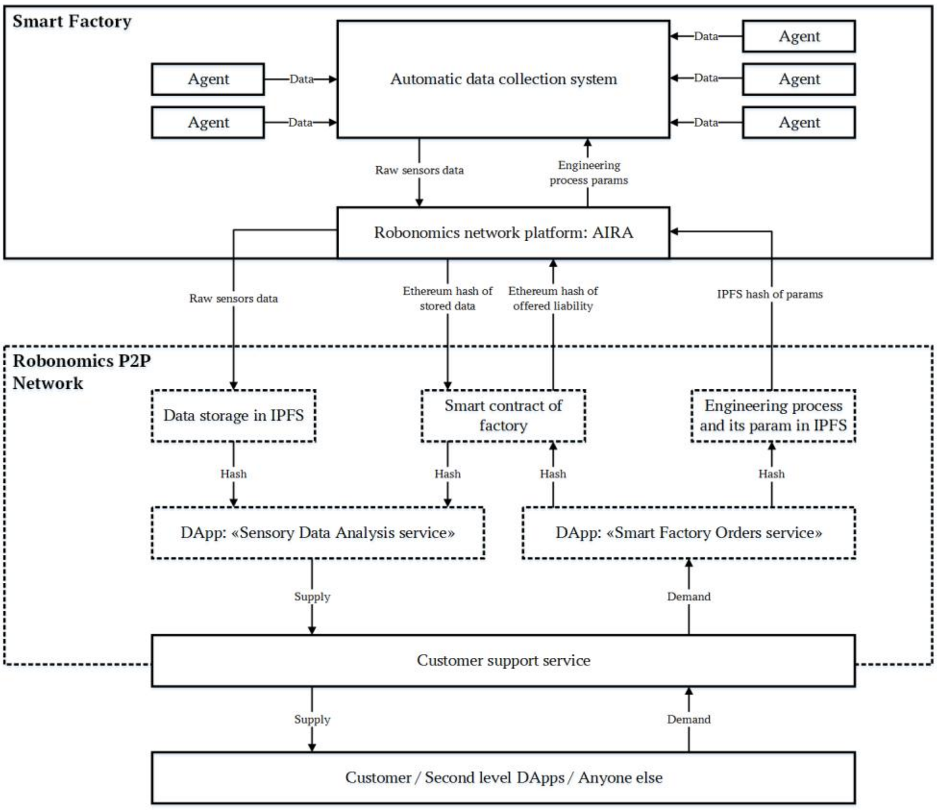

Figure 2. The process of smart factory operation: the dashed line shows the nodes of decentralized systems

The economic process is that factories are adjusted to market changes trying to produce more products for those with higher capital. In case of unsuccessful choice, the production of factories does not manage to be sold and warehouses are overflowing.

VIII. Conclusion

In the article, we presented and justified market methods of organizing the work of autonomous agents in smart factories. As a technological basis, Blockchain technology was proposed. Its advantages are described and the applicability of decentralized technologies for smart factories is demonstrated. Various levels of the proposed platform were considered: from the general work of the protocol to the operation of individual agents and the technological process of the whole factory.

In the near future, the world expects a significant integration of cyber-physical systems into everyday life, into the work of cities and industries.

We believe that the organization method we have described and the technology platform are potentially capable of answering future challenges. The implementation example of our methods mentioned above illustrates the opportunities of the platform and proves its viability.

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