Blockchain based protocol for economical communication in Industry 4.0

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***Abstract*—The article presents the architecture of communication protocol for modern industrial processes and business based on cyber-physical systems — Industry 4.0. The main attention is paid to one of the key trends of this concept — to economical autonomous agents i.e. to robots or smart things, which are able to make decisions independently about their economic actions. Agents begin to fully participate in business processes, so it is important to automate the processes and ensure formal and secure communication between multiple heterogeneous agents, taking into account the economic component of the industry. The article shows how to organize economic interaction between agents using a peer-to-peer network based on decentralized Blockchain technology and smart contracts. The general concept of protocol work is described and the experience of its implementation on ROS and Ethereum Blockchain is presented in the form of universal software for different agents. As a result, the experience of applying this solution in various projects is described: a business project with unmanned aerial vehicles (UAV) and an educational project of "smart city".**

I. Introduction

Today industrial processes and a significant part of business processes are on the way to full automation. The explosive development of cyber-physical systems (big data, autonomous robots, Internet of Things, etc.) and their introduction into industry resulted in the idea of Industry 4.0 as a new approach to production and entrepreneurship [1].

Let's take a look how autonomous robots and smart things (which we combine into the concept of autonomous agents) become participants of business processes and modern industry [2]. Nowadays, the process of production, delivery and sales is accompanied by transactions in digital registries using corporate networks and the Internet [3]. Some of these transactions are related to contractual liabilities and the transfer of ownership rights from executors to customers, from producers to consumers. Completing this system with autonomous agents which have the right to choose their actions and interact with each other and with people, leads to the fact that agents also become participants of economic relations [4], for example, a network of automatic taxis, independently charging fees for the service.

In addition, autonomous agents in a multi-agent system are exposed to additional security and safety risks both for the system itself and for the surrounding world, [5] because of potential attacks by intruders or network failures. The fact that agents participate in economic processes only increases risks and costs.

Thus, we consider a model where agents interact with each other in a multi-agent system on the one hand, and on the other hand, exchange regular liabilities and transfer ownership rights as participants of business processes. This model can be considered as a multi-agent system [6], consisting of smart things and robots that automatically put data into the digital transaction register. All this leads to the fact that the activity of agents must be carried out in a safe, unified environment, tied up in economic interaction.

For large business processes, business launching can not do without a common information system where participants can trust each other [7]. Often this information system is a centralized service, imposed by state agencies. However, this entails an increase in the number of intermediaries, which complicates the process of storing and changing information about liabilities and ownership rights [8].

If we add autonomous agents to business processes, transaction costs and risks connected with errors in the information transfer between information systems are greatly increasing. Also costs will increase due to the centralization of the control over agents [9], because a system failure of the center or its capture by intruders will lead to paralysis of the work.

Direct communication between agents solves these problems [10]. But in this case there is a question of trust between the interacting participants: in the case of disagreement, the parties of the conflict have an ability to locally change the stored information about liabilities to their side [11].

In 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 [12] 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 [13] of the Industry 4.0. Thus, there is already a request for a safe and efficient way to organize the work of autonomous agents.

So there is an open question: how to create a suitable model for secure interaction of autonomous agents, which would allow storing and transferring liabilities and ownership rights [14]. In addition, in our opinion, new questions arise concerning the participation of autonomous robots in economic processes. How to ensure the transfer of ownership rights to a consumer, if the process of production and logistics does not

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involve people? How can a fully automated factory understand the changing needs of people? How to charge taxes from the activities of robots and what should be considered a separate robotic unit?

II. Decentralized technology

As already noted, the introduction of a direct information exchange system solves the problem of transaction costs for autonomous agents, but it is necessary to ensure the security of this system. And we consider Blockchain technology as an excellent candidate for creating an information system for all the participants in a single business process [15], [16]. It allows creating a peer-to-peer decentralized network for multiple agents [17] with an information protection mechanism what covers the need for security for Industry 4.0 [17], [18]. Blockchain has an ability to track data changes and protect transactions, and third-party authentication is not required to get started. The user identification is limited to the local generation of cryptographic transaction keys. We chose a public Blockchain, because a permissioned one promotes formation of cartels and it is much less suitable for creating economic networks of a planetary scale.

This allows you to organize an independent arbitration of all the participants in the digital registry while maintaining the publicity of the relationship between the participants. Independent arbitration guarantees that any actions of business process participants correspond to the current state of local repositories of all the participants. Therefore, a network organized by autonomous agents will be protected from changes caused by a faulty data source, individual participant, or external intruder.

At the same time, Blockchain has shortcomings [19]. There are system problems caused by the very principle of network consistency. This leads to soft / hard forks when the rules for reconciling the functioning of the network change, what leads to the loss of already approved information. This can be exploited by intruders, but attacks on Blockchain require quite powerful computing resources. The legal status and mechanisms of legal protection for participants of the supply chain and their resources are still unclear. Blockchain has a status of just appeared technology, but a large number of researchers and developers are constantly improving it, and it seems to us, that most problems will be solved soon.

III. Smart contracts

One of the advances in the development of Blockchain technology is smart contracts performed by the virtual machine in a decentralized network. For the first time, this approach was demonstrated in the development of the Ethereum protocol [20]: it can be used to program an autonomous agent in real-time within a decentralized network. The protocol allows to write any custom logic, save data from transactions into a public Blockchain with an independent arbitration. Due to the possibility of programming in public Blockchain, we can ensure a fully automated interaction of agents, giving them an ability to fulfill liabilities and transfer ownership rights, without the risk of changing, eliminating or violating the rights of access to data. It should be noted, that this principle is the basis of the concept of Decentralized Autonomous Organization (DAO).

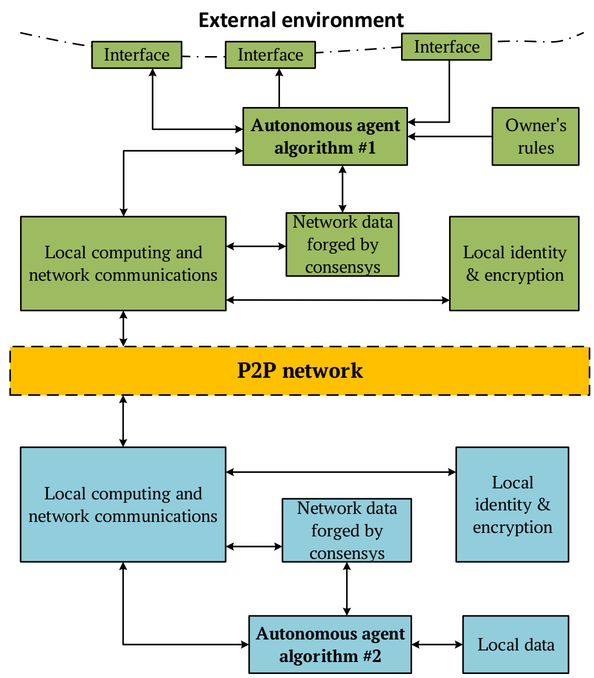

Fig. 1. The architecture of agents' interaction protocol. The arrows indicate the transfer of data. The dashed line shows a peer-to-peer network. The dotted line shows the external environment

The principle of smart contracts fully correspond the needs of business processes with autonomous agents [21], [22], up to the forecast of sales and the formation of supply networks. For example, the article [23] describes the mechanism of predicting markets with the use of the futures on the market volume estimate.

IV. The architecture of economic interaction protocol

Fig. 1 shows two agents interacting with each other using a peer-to-peer decentralized network. Interaction with the environment is carried out through interfaces. In addition, the architecture has a mechanism for direct agent control, but in general, the agent doesn't have to have interfaces to the world around it or mechanisms to control its actions. User authentication is provided by the special external interface.

It should be emphasized that the interaction of agents occurs exclusively through a peer-to-peer network. Also, the structure of the system implies two types of data: local data of agents and network data forged by contracts. Agents may have no local data, but network data is mandatory for them. This assumes the use of light blockchain clients [24], to save the agent's memory.

Concluding a contract with an agent requires tokens of decentralized network. After executing a transaction with a required number of tokens, the agent starts executing the algorithm laid down in the smart contract. A series of smart contracts concluded between agents and between people and agents, forms a desired business process. And the advantage of this system is that all potential critical situations (an error in the contract code, a lack of tokens to complete the execution, etc.) can be preliminarily or in the process resolved, by entering additional contracts. To ensure successful completing transactions of agents in the system, it is proposed to set a time delay.

V. Implementation of the Protocol

In 2015, we developed the project AIRA (Autonomous Intelligent Robot Agent), which implements the standard of economic interaction human-agent and agent-agent through an intellectual liability contract. AIRA enables many different agents to be connected to the liability market for the direct sale of data from agent sensors, ordering unmanned transportation services, organizing the order of personalized products at robotic enterprises and any other work that autonomous agents are capable to perform. In terms of security requirements, AIRA works in the industry infrastructure and inherits all of its requirements.

Technologically, the project links the smart contracts of Ethereum network and any agents that are compatible with the high-level industrial communication framework Robot Operating System (ROS). For Ethereum Blockchain connection to the physical sensors we use OPC Unified Architecture and native drivers. To store data, the system uses a distributed file system IPFS (InterPlanetary File System). AIRA uses its own tokens within the network — Robonomics Utility token, as well as tokens of Ethereum — ether token. Performance requirement for agents: sufficient amount of RAM and disk bandwidth for Ethereum Parity client.

For low-level communication between smart contracts and autonomous agents, a package for ROS and a set of smart contracts Ethereum were implemented, allowing smart contracts to interact with nodes of the robotic system as if they were a part of it. This allows us to unify the protocol of interaction. Thus, the first level of the software consists of: contract *ROSBridge*: Ethereum network access point for agents; **aira_ros_bridge**: application for low-level interaction with a smart contract.

Higher levels of software (Cognitive service, Market analytics and Management service, etc.) are responsible for fulfilling tasks related to economic and productive activity. The first one is implemented as a neural network and is engaged in work planning. Due to its resources, more specialized services work. Market analytics, for example, analyzes the entire network of autonomous agents and chooses the most cost-effective task for the agent. To perform a specific jobs (flight, cargo transfer, etc.), an agent uses Management service, which loads the necessary sets of solutions from the repository.

The typical process of forming a liability for a robot is as follows in AIRA project: formalization of the goal, formalization of the goal results in the form of records in Blockchain, validation of results based on the goal.

To formalize a contract liability a unified contract of autonomous agent, *RobotLiability*, was developed. This smart contract provides the basic interaction of ROS-compatible agent, employer and owner of the agent so that: 1) the employer complies with the liabilities of the contract; 2) the agent receives a notification about the payment for the service

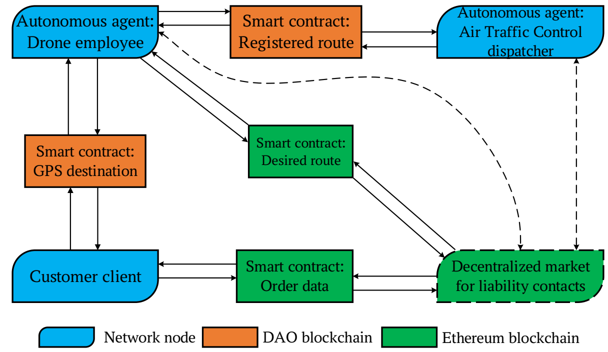

Fig. 2. The scenario of an order. The dotted arrow indicates the expectation of the contract appearance. All the contracts in the network are collected in a decentralized contract market

and publishes the result of the work (in the form of a hash); 3) tokens are sent to the beneficiary only after the publication of the work results (in the form of a hash) and validation.

Successful computer simulations and test projects were performed in which autonomous agents were given some simple task, and then an autonomous business process was launched (automatic production, smart city, etc.). The results of the experiments are presented in [25].

VI. Protocol Applications

In 2016, we created the first commercial project based on AIRA — Drone Employee. In the project, Unmanned Aerial Vehicles (UAV) and dispatchers act as autonomous agents. We create a supply chain between service customers, UAV and various dispatcher services that reserve air routes for UAV based on waypoints. The dispatcher works with topographic data, traces the route in the 3D-map and places it in Blockchain. UAV obtains waypoints from the transaction and performs the flight.

A typical scenario for completing an order is as follows (figure 2).

A customer makes out a request for the performance of any activity (filming, delivery, etc.). This generates a smart contract with the order data (order purpose, customer data, etc.), then this data is loaded into the distributed file system of the liability market. UAV of any company that provides the activities necessary for the customer can take on this contract. After that, a smart contract is directly concluded between the customer and UAV containing the data of the client's location.

UAV commits a transaction to the liability market, requesting an air corridor from the Air Traffic Control. As soon as there is a dispatcher who agrees to accept this contract, a new contract is concluded between them, containing data of the registered route. UAV makes a planned flight and informs the customer about the performance of the work. After returning to the base, UAV notifies the dispatcher that the air corridor has been used up. For this project, successful field tests were conducted with real drones. At the moment, the project is launched and successfully operates [26].

Another example of using our protocol is an educational project Duckietown for training robotics [27]. The project was launched in 2016 and is now used in approximately 20 universities around the world, including Innopolis University. On the hardware side, the project itself includes small autonomous agents — "Duckiebots" — simple autonomous robots and the infrastructure in which robots move. One of the tasks of the project is modeling urban traffic, and for this purpose the process of taxi service was considered.

Let's consider a customer, who orders some taxi service. He draws up a smart contract with a taxi service provider i.e with a network of autonomous agents. The customer performs a transaction with a description of the goal — in this case, the point of arrival. The agent executes the task and sends transactions in which all the operations performed by it are recorded. Finally, the software that performs the function of the protocol validator compares the goal and the result and makes a decision: if the liability is fulfilled or not?

VII. Conclusion

In this article, we provided an architecture for creating a protocol for economic interaction of autonomous agents involved in business processes. We examined Blockchain technology and smart contracts as potential candidates for organizing secure interaction between autonomous agents. We presented our experience in implementing this protocol in the form of software, as well as the experience of implementing business and educational projects based on our decision, which proves its operability.

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