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Blockchain-based protocol of autonomous business activity for multi-agent systems consisting of UAVs

Aleksandr Kapitonov[1], Sergey Lonshakov[2], Aleksandr Krupenkin[3] and Ivan Berman[4]

Abstract— **This article describes a method of organizing the communication protocol, which allows agents of the multi-agent system (MAS) to make decisions about their actions. Plan activities and interact with each other to perform tasks of modern industrial and business processes based on cyber-physical systems. The main attention is paid to those multi-agent systems, where autonomous agents — robots or smart things — participate in business processes among people, and their activities are organized in an unreliable and unknown environment. The article shows, how to organize a communication system between agents in a peer-to-peer network using the decentralized Ethereum Blochchain technology and smart contracts. The architecture of protocol of autonomous business activity, based on this communication method is given. As a result, the experience of implementation an autonomous economic system with unmanned aerial vehicles (UAV) is described.**

Index Terms— **MAS, cyber-physical systems, Ethereum Blockchain, smart contracts, ROS, AIRA, P2P network, UAV.**

I. INTRODUCTION

The development of modern industrial and business processes is on the way toward a full automation due to the active penetration of information technologies into these areas. The total introduction of cyberphysical systems (autonomous robots, big data, Internet of Things, etc.) is just a matter of time [1], and the main question facing developers and researchers is how to make this process as simple and safe as possible. [2].

Autonomous agents, combined into the multi-agent system, in which agents exchange data with each other and perform work, play an important role in modern automation of business processes [3]. Now, software agents are already used in business: trading bots, data collectors, etc. Further development of this trend will result in a situation, where robotic multi-agent systems (whether mobile robots or smart things) will be universally used in the industry and business, which will also actively be involved in business processes [4].

This development is promoted by a number of reasons. A huge scale of industrial and economic works has led to the fact, that centralized management of agents faces a complicated process of storing and changing information. Transactional costs and risks associated with errors in the information transfer, a system failure of the center or its capture by intruders, are greatly increasing [5]. The most significant is the fact that such agents must perform their function near people [6]-[7], what imposes additional factors on the multi-agent system safety. In addition, there are industrial tasks that must be solved by the agents of heterogeneous origin [8] (for example, an unmanned aerial vehicle and a manipulator, which perform loading and delivery of cargo).

Thus, we are considering a multi-agent system [9] consisting of smart things and robots, which share data safely, directing each other's work. In addition, for large business processes the work of autonomous agents cannot be done without a communication system which can provide safe and unified communication between the participants. At the same time, such a system should be easily scaled satisfying the requirements of growing industry and business.

Summarizing the foregoing, there is an open question: how to create a suitable protocol for the autonomous agents? activities in a multi-agent system that would cope with the requirements of modern industrial and business processes [10]. This protocol should ensure a secure level of communication between agents and help to develop adequate solutions for changing working conditions.

II. BLOCKCHAIN TECHNOLOGY

One of the possible foundations for creating a secure protocol for autonomous business activity, in our view, is the Blockchain technology [11]. This technology allows creating a peer-to-peer decentralized network with an information protection mechanism [12], and this network will perform the function of a secure communication system within the multi-agent system [13]. Blockchain has an ability to track data changes and protect them, and a third-party authentication is not required to get started. The user identification is limited to the local generation of cryptographic keys of transaction, being committed into the network.

Each agent of the network owns a shared distributed database, which consists of the chain of information blocks, in which each current block is connected with the previous block using a unique cryptographic identifier. Adding a new block to the database is impossible without the agreement between all the agents — this mechanism is called consensus [11]. It guarantees that any action of the agent corresponds to the current state of the local repositories of all the agents. Therefore, the communication between autonomous agents will be protected from the changes caused by a faulty data source, an individual agent or an external intruder. In such a case, each agent in the network will have equivalent rights.

However, Blochchain has shortcomings [14].

[1]Aleksandr Kapitonov is with ITMO University, 49, Kronverkskiy prospekt, Saint Petersburg, Russian Federation, 197101, Email: kapitonov.aleksandr@corp.ifmo.ru

[2]Sergey Lonshakov with Airalab — aira.life, Email: sergeylonshakov@gmail.com

[3]Aleksandr Krupenkin with Airalab — aira.life

[4]Ivan Berman with Drone Employee — drone-employee.com, Email: bermanivan42@gmail.com

First, the principle of network consistency generates disruptions and discredit. This leads to the events called solf / hard forks [14], when the rules for the functioning coordination of the network change, what leads to the loss of already approved information. Intruders can exploit this, but attacks on Blockchain require quite powerful computing resources.

Secondly, the legal status of this technology has not yet been determined. Since autonomous agents must participate in economic processes, this can lead to legal problems. Fortunately, state regulators of different countries are already dealing with this issue.

And thirdly, it is worth noting that Blockchain has appeared relatively recently and the technology is in the crude stage, 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. COMMUNICATION BETWEEN AGENTS

One of the important technologies that emerged during the development of Blockchain is the technology of smart contracts which are performed by a computer device in a decentralized network. For the first time, this method was demonstrated in the development of the Ethereum protocol [15]: it can be used to transfer commands between agents in the form of data or executable code in real-time. The protocol allows writing any custom logic, and then saving the resulting algorithm and data into a public Blockchain. Due to the possibility of programming in the public Blockchain, we can ensure the fully automated communications between agents [16], through which agents can deal with each other and execute commands.

Now we will introduce the architecture of the communication system between autonomous agents within the multi-agent system. Fig. 1 shows two agents communicating with each other using a peer-to-peer decentralized network. To interact with the environment, an interface mechanism is provided for the agent. In addition, in architecture there is a mechanism of influence on the agent, being committed by the developer. However, in general, the agent doesn't have to have interfaces to the world around it or mechanisms to control its actions.

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 agent and network data protected by a smart contract. Agents can have no local data, but network data is mandatory for them. Also, each agent performs the necessary identification and data encryption for the proper operation of the Blockchain.

The conclusion of a contract with an agent requires tokens of this decentralized network, which can be considered the internal capital. If the first agent makes a transaction with the required number of tokens, the second agent will execute the algorithm laid down in the smart contract. A series of smart contracts being concluded between agents forms a system of communications in a multi-agent system.

Such a system will be protected within the Blockchain technology boundaries, but there are several nuances. First, the code inside the contract may contain an error. Also, there may be a situation, when agents in the already running chain of contracts do not have enough tokens to complete their liability. These problems can be solved by entering additional contracts, which determine scenarios of interaction between agents in critical situations. To ensure successful passage of transactions in the system, it is proposed to set a time delay.

The next section will describe how we use this communication method to create an autonomous business activity protocol.

IV. PROTOCOL ARCHITECTURE

In 2015, our team developed the project AIRA (autonomous intelligent robot agent) [17], which embodied the blockchain protocol of economic activity for multi-agent systems. AIRA deals with the formalization of interaction and data exchange between robotic networks and smart contracts [18]. The protocol allows you to connect a variety of different agents to a general network in which each agent can request and offer different services — transfer of data from agent sensors, moving to a desired point, cargo transportation and any other work that autonomous agents are able to perform. The service can be requested either by an agent from another agent or by a person who has the protocol installed on the computer.

It should be understood, that the protocol is suitable for the agents involved in any activity, whether commercial, income-producing agent owners, or non-profit, where a secure protocol of any activity is necessary.

Technologically, the project links the smart contracts of the Ethereum network and any agents which are compatible with the high-level industrial communication framework Robot Operating System (ROS). To store data, the system uses the distributed file system (IPFS) (InterPlanetary File System), to whose files agents also access with cryptographic identifiers. To conclude transactions between agents, AIRA uses its own tokens within the network (air-token) and tokens of the Ethereum network (ether).

For the connection between a smart contract and a robotic system, we implemented a ROS application — *aira_ros_bridge* — for low-level interaction with a smart contract.

The architecture of the AIRA protocol is shown in fig. 2. The protocol is implemented in the microservice paradigm using the Docker virtualization system, and the level of complexity of the microservices increases from the bottom to up. The supervisory function over the entire system is performed by the AIRA Kernel microservice, which is duplicated for the prevention of system failures. AIRA P2P service is responsible for interaction with other AIRA instances. IPFS and Ethereum services are responsible for working with the appropriate networks. The main work on finding solution and planning works is performed by Cognitive service, which is technically implemented as a neural network. Its resources are used by the services, which require cognitive work from

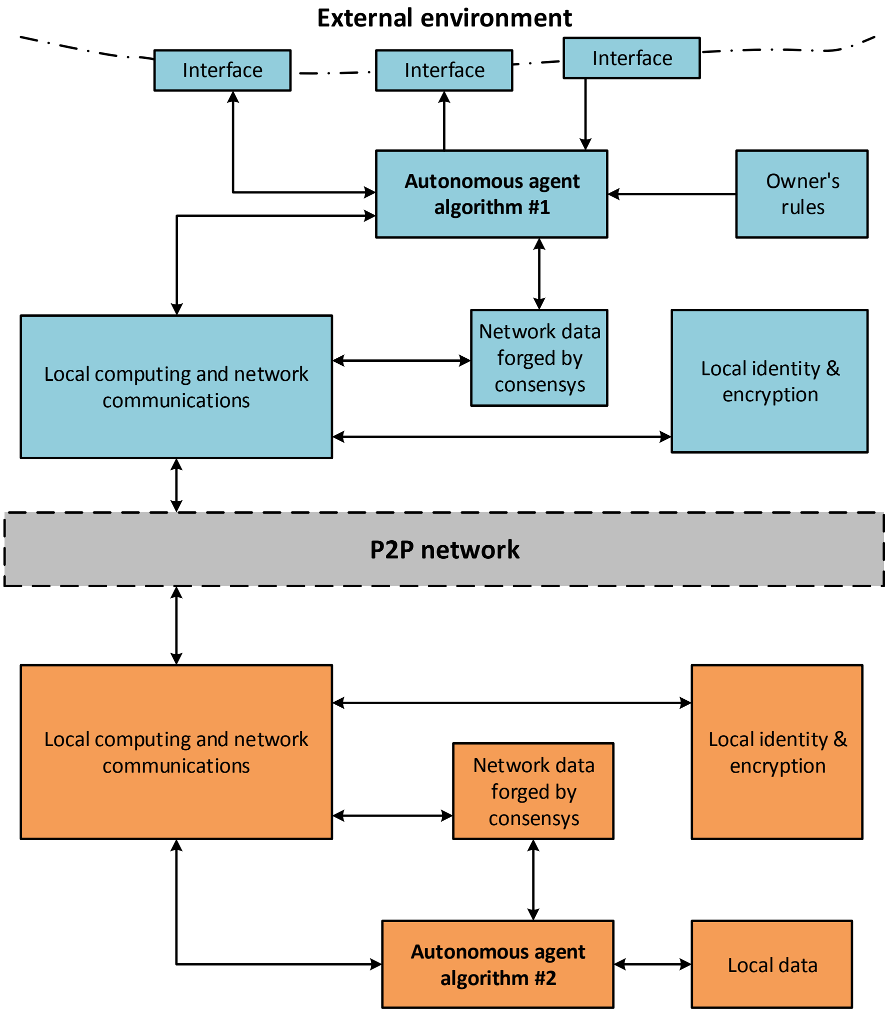

Fig. 1. Autonomous agents communication scheme. The arrows indicate transfer of any data. The dashed line shows the P2P network between agents. The dotted line shows external environment of the agent.

an agent, first of all — Package adviser and Market analytics. The first one looks for and analyzes the software packages necessary for the agents? work. The second performs an analysis of service offers from other agents and tries to predict further changes in network. Based on this, the service chooses the most beneficial strategy of action.

To ensure the uniformity of the protocol for different models of robots or smart things, Adapter analysis is implemented in protocol: it analyzes and searches drivers for actuators or sensors of autonomous agent. Remote Adapter microservice is responsible for connecting to them.

Since agents can be heterogeneous in their functionality, we have provided a special repository that stores solution sets for various kinds of management tasks, whether it is a UAV flight or execution of industrial operation by a manipulator. It is assumed that this repository will be supported by us and the developers' community.

To formalize the transaction between agents, a unified contract was developed — *RobotLiability*. This contract provides a basic interaction between an employee, an employer, and also the owner of the robot in such a way that:

1) the employer complies with the terms of the contract;
2) the employee receives a notification about the payment for the service and publishes the result of the work (in the form of a hash);
3) air-tokens are sent to the owner only after publication of the work results (in the form of a hash).

The AIRA protocol was successfully tested in computer simulation, where the autonomous agents needed to perform a simple task of moving from one point to another. The results are presented in [19].

V. EXPERIENCE OF APPLICATION

In 2016, we used the AIRA protocol to develop the Drone Employee project [20], aimed at creating an infrastructure

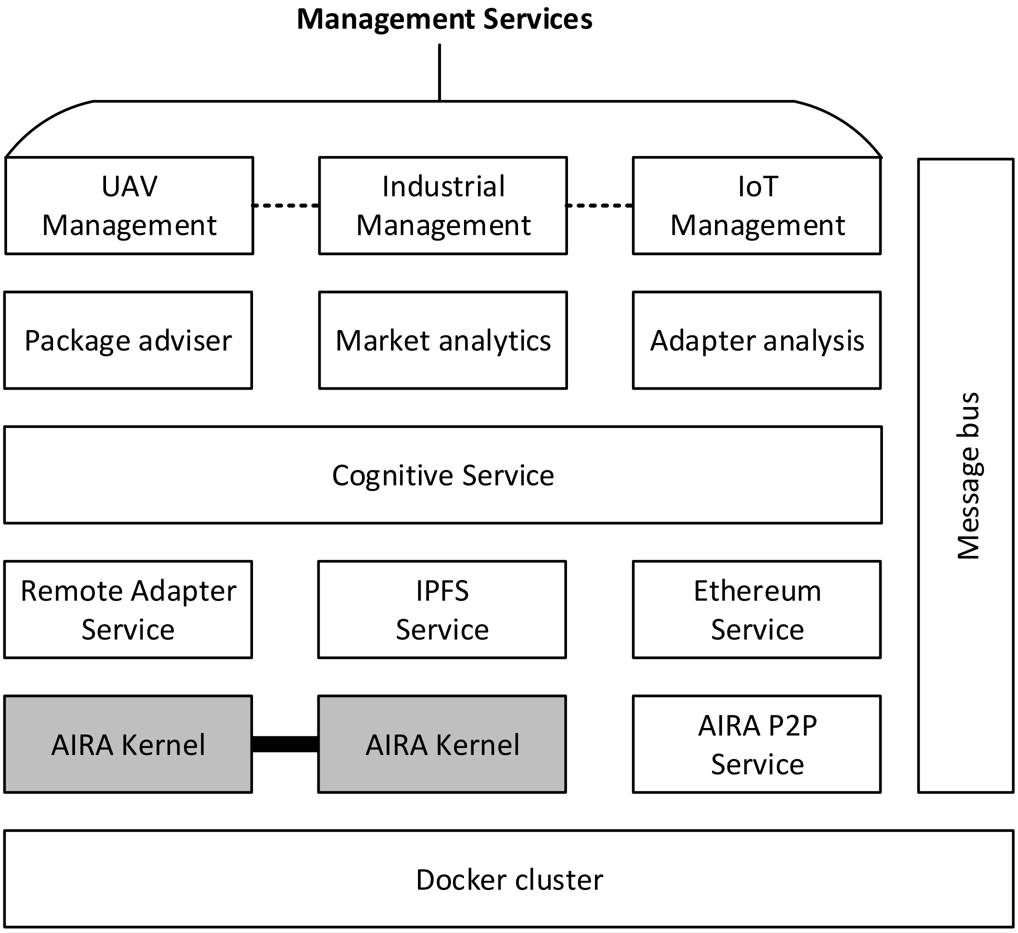

Fig. 2. The architecture of the AIRA protocol.

operator system in the field of navigation, regulatory and economic activities using UAV to ensure the unity of technical management and airspace regulation. This project establishes communications between the UAV and various dispatcher services that reserve air routes for UAV based on waypoints. Dispatcher works with topographic data, traces the route in the Digital Elevation Model (DEM) and places it into Blockchain. UAV receives waypoints from the transaction and performs the flight.

In Drone Employee, the autonomous agents are UAVs and service-nodes, located on the ground. In the system, they are divided into two types of nodes. Air Traffic Control (ATC) is a node which performs a function of a ground dispatcher that directs aircrafts by assigning them safe flight routes over the designated area. The second node — Unmanned Traffic Management Balancer Watcher — is a supervisor node that regulates the operation of ATC nodes and distributes responsibility for the airspace between them.

A typical scenario of agents work is shown below (fig. 3). A UAV-agent or a person makes an order for filming / delivery. A smart contract is generated with the order data (the purpose of the order, client data, etc.) and then transferred to Ethereum Blockchain. Any free UAV-agent can accept this contract for execution. After that the client and the UAV-employee conclude a smart contract for air tokens, that contains the information about the client's location.

Then UAV commits a transaction to the market of liability contacts to provide an air corridor to the agent-dispatcher. As soon as the dispatcher, who agrees to accept this contract, appears, a new contract is concluded between them, containing the information about the registered route. UAV-employee makes a scheduled flight and informs the client about the performance of the mission. After returning to the base, UAV notifies the dispatcher that the air corridor has been used up.

For this project, successful field trials were conducted with real drones [21]. At the moment, the project is launched and successfully operates.

VI. CONCLUSIONS

In this article, we provided an architectural solution for organizing a business activity protocol for multi-agent sys-

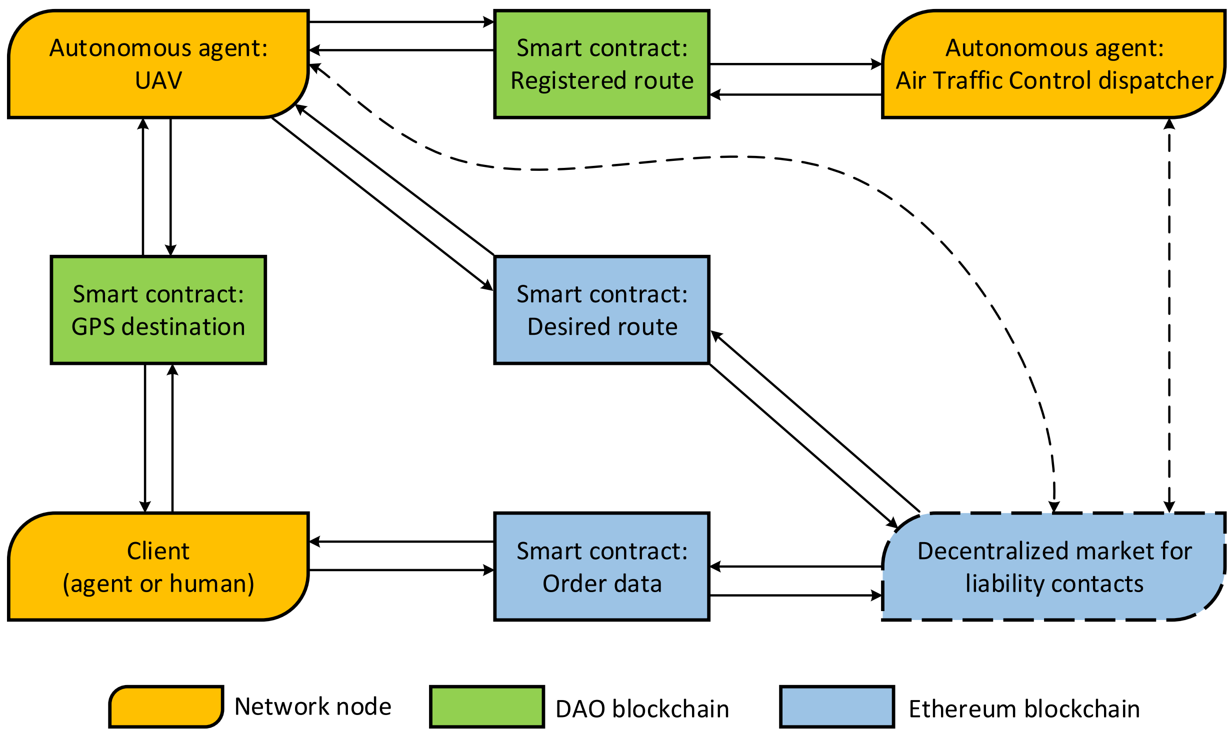

Fig. 3. Typical work scenario of Drone Employee. Dashed arrows indicate waiting of contract appearance. A set of all contracts in the network are integrated into decentralized market block.

tems. We reviewed the Blockchain technology and smart contracts as potential candidates for organizing a communication network for autonomous agents. A method of communication between autonomous agents was suggested and implemented with the help of these technologies. The architecture and function of the protocol were presented, based on the proposed method of communication. We also described the experience of implementing this protocol into a multi-agent system with unmanned aerial vehicles, which proves the viability of our solution.

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