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Robonomics as a Blockchain-based Platform for Unmanned Traffic Management of Mobile Vehicles

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***Abstract*—The article describes the concept of a decentralized architecture of a traffic management system for mobile vehicles and is a continuation of the results presented in the previous article ”Blockchain-based protocol of autonomous business activity for multi-agent systems consisting of UAVs”. Robonomic protocol is the basis for the system architecture — a combination of the decentralized Ethereum computer, the IPFS distributed file system, Robot Operating System and market mechanisms. In particular, its focused on the principle of communication between nodes of the traffic management system and the stages of the unmanned mission. As a proof of concept, two experiments on the integration of the proposed architecture are presented: air quality measurements using unmanned aerial systems (UAS) and water quality measurements using unmanned surface vessels (USV). Our work demonstrates that distributed ledger and smart contracts technologies are applicable to the traffic management system and increases the transparency and immutability of the data.**

I. Introduction

In recent years, the idea of introducing cyber-physical systems (CPS) has aroused wide interest in almost all areas of the economy, production and public sphere [1]. Smart devices of the Internet of Things are able to notify the owners about their condition using network connectivity and respond to changes in the environment. They have been successfully launched into mass production. Networks of compact sensors that optimize power consumption and transmission are integrated into the urban infrastructure. Intelligent manipulators are used in industry and medicine. Developers, researchers, and experts are already developing various concepts of Smart Cities where autonomous agents are integrated into a shared network to perform a wide range of tasks [2].

To the greatest extent, the potential of cyber-physical systems is revealed through the use of unmanned aerial, ground and water vehicles, machines and robots. Mobile autonomous agents allow solving critical problems in the design of smart urban infrastructure. One of the big challenges for humanity is environmental pollution. The increase of the urban population adversely affects the ecological situation, up to severe consequences, and now the global level of urbanization has already exceeded 50% [3], [4]. Therefore, environment management and environmentally friendly infrastructure have become the most important elements of Smart Cities, and it requires constant monitoring of the state of the environment [5]. A monitoring system can be organized using a UASs and USVs equipped with compact sensors. The civil monitoring concept is based on this idea, and even if mobile agents with compact sensors are not accurate enough compared to expensive laboratory equipment, such monitoring systems will be able to provide operational signals about changes in the environment [6].

The large-scale implementation of mobile autonomous agents is still the subject of discussion, and most developments in this area are at the prototypes and experiments stages. The need for precise unmanned traffic control systems for mobile agents is among the reasons due to which the use of unmanned technology is slowed down [7]. This is the question we want to focus on in this article. A system should be responsible for the information coordination of agents, for the safe routing, for tracking the missions, for communication with regulatory authorities and for other functions. At the same time, additional critical requirements are imposed on the traffic management system, unlike the existing traffic control systems.

At first, safety is one of the most important issues [8]. The multi-agent system of unmanned vehicles requires a reliable method of their identification and a mechanism for protection against cyber attacks. Second, the number of connected devices is expected to exceed tens of billions (the number of IoT devices is estimated to be 75 billion by 2025) [9]. Therefore, the fast scaling mechanism should be the basis of the traffic management system architecture [10]. Third, the problem of heterogeneity of a multi-agent system arises, caused by the hardware variety of autonomous agents [11]. Finally, significant and confidential information from devices should be verified and protected, especially when it comes to legal use and the citizens privacy [8].

In this article, we show the vision of a traffic management system for autonomous agents with transparency and immutability of the information. In section 2 the current state of the field in research and development of traffic management systems will be described and in section 3 the reasons for why proposed system fits the emerging requirements will be explained. In section 4 the principles of communication of nodes in the traffic management system will be described and the system architecture in section 5 will be proposed. In the last sections, examples of implementation of unmanned aerial and marine vehicles for environmental monitoring will be shown.

This work is a development of the ideas described in the article "Blockchain-based protocol of autonomous business activity for multi-agent systems consisting of UAVs", where we described the decentralized communication protocol for the UAV swarm and "Robonomics Based on Blockchain as a Principle of creating Smart Factories" where the topic of managing autonomous agents in smart factories was expanded [12], [13]. The current one differs from previous works by focusing on the architecture of the traffic management system, a more detailed description of the mechanism of communication between agents and the expansion of the implementation across the whole range of cyber-physical devices.

Our paper differs from such works as [14] in that it is a proof-of-concept of the architecture of the decentralized traffic management system itself, rather than a specific implementation of the traffic management system. The article differs from other works (such as [15]) by a decentralized approach to building a traffic management system.

II. Pitfalls of Unmanned Traffic Management

The pitfalls in building architecture for traffic management is most clear for UASs, commonly called drones. In recent years, due to the emergence of fairly cheap UAS models, researchers have become more actively engaged in developing control systems for their movement. The potential of UASs for business is obvious, however, state civil aviation authorities and security agencies of various countries have limited the use of drones until a reliable infrastructure appears.

NASA researchers, in conjunction with experts from the US Federal Aviation Administration, established three main paradigms that must be followed in developing a UAS traffic management system: protecting national interests, safe flights ensuring, and preserving economic progress [10]. After a series of prototypes, the NASA UTM team developed the following characteristics required for a traffic management system: 1) unambiguous device authentication; 2) a standardized protocol for exchanging data and information with pilots and regulators; 3) flights on pre-set routes; 4) integration of weather data and 3D maps; 5) a mechanism to avoid obstacles and other aircraft; 6) emergency management mode; 7) route optimization for heavy traffic [10]. In this case, the researchers focused on the scalability of the system.

Researchers at the MIT International Center for Air Transportation think that the main problems of controlling unmanned traffic are the increase in the number and density of operations, as well as the variety of models of aircraft devices [16]. The authors of [17] also pay attention to the issues of route congestion and the need to increase the automation of traffic optimization tools.

III. Traffic Management and Robonomics

Earlier, our colleagues developed a Robonomics protocol for the organization of secure communications in a multi-agent system [18]. The protocol is based on the market mechanism of communication between network nodes and the use of p2p-technologies: the decentralized Ethereum computer and the InterPlanetary File System (IPFS) distributed file network. With Robonomics we organize a secure network of cyber-physical devices where each node has a cryptographic identifier, any important work of the nodes is logged and all information is stored and protected, and the results of the work can be verified. The protocol key concepts are:

- Liability Market. Supply and demand between nodes are matched here. Market access is organized through IPFS messages.
- Liability Contracts — smart contracts made by cyber-physical systems with each other or a person.
- Tokens. Since the interaction is based on the market mechanism, there are cash equivalents in the network.

In one of the previous works, we presented the successful connection of UAVs using this mechanism [12]. Then, taking into account the requirements for unmanned traffic management systems, we analyzed the possibility of creating an effective traffic management system based on the Robonomic protocol. We have identified the following benefits:

- System can uniquely authenticate all autonomous agents in the network due to the cryptographic ID.
- The market mechanism of nodes coordination facilitates the task of distributing and registering agents routes and also opens up good opportunities for optimization methods. An important fact is that such a structure is easier to integrate with the real business process.
- Adding any services necessary for traffic management (3D maps, weather data integration, etc.) is supported because each element of the system is represented by a separate node.
- The decentralized paradigm allows you to organize the work of nodes so that the failure or hacking of network nodes does not lead to disastrous consequences [19]. For example, hacking an autonomous agent will not compromise other agents or the entire network: a damaged agent will be detected and forced out of the network. In case of hacking of the unmanned traffic management system, the traffic will certainly stop (if there are no duplicate management nodes), however, the agents will not perform an unreliable mission due to the inconsistency of data in the distributed ledger.
- The decentralized approach to building the architecture of unmanned traffic, on the one hand, reduces the computational load on the control system, and on the other hand, allows connecting more devices than the centralized approach [20].
- The problem of device heterogeneity is solved by using the Robot Operating System (ROS). For new devices, it is only necessary to create an integration package with ROS.
- The cryptographic uniqueness and security of the protocol guarantee the security of private and public interests and the privacy of participants. The distributed ledger mechanism forced out network nodes that break rules of airspace usage. Due to this, we can talk about the possibility of its use on a transnational scale.

The main disadvantage of this approach is that in case of emergency situations (for example, natural disasters or terrorist attacks), the decentralized management loses in speed in comparison with a centralized approach. This question is open: how to keep the benefits of decentralization, but at the same time leave the possibility of a rapid response to incidents. Possible solutions: creation of a special token and a set of smart contracts for emergency services, but more research is needed in this area.

Below we describe the main mechanisms and components of a traffic management system built on the basis of the Robonomics protocol. Our work reveals the principle of identification of agents, communication between them and traffic management nodes, and nuances of route distribution between agents. We dont consider the problem of finding and avoiding obstacles, but the problem must be taken into account for a complete traffic management system. However, software and hardware designed for this purpose can be easily integrated into the network as a separate node and added to the workflow chain.

IV. Principle of Nodes Communication

Special software (AIRA client) was developed for the protocol that enables the connection of the Robot Operating System with Ethereum and IPFS. Also AIRA is responsible for connecting the CPS to the Liability Markets.

We briefly describe the principle of operation of the protocol, and list the nodes involved in a typical scenario:

- *A promisee* is a node that orders a certain service (for example, measuring air quality at a specific point). This can be both human and software.
- *A promisor* is a node that is ready to accept a task. It can be associated with both physical work and software tasks.
- *A provider* is a node that monitors the message channel in the Liability Markets and for the commission finds matching supply and demand. Providers of one channel are managed by the *Lighthouse* — a smart contract defining the work of Providers (for example, Lighthouse distributes the operating time of providers). Lighthouse receives a transaction from the Provider when it establishes a market match.
- *A validator* is an optional node that can be a person or a CPS. If the Validator is specified at the time of liability conclusion, then only it can complete it after checking that the work is done.

The work process is performed in three stages (fig. 1). At the first stage called Negotiation, Promisee sends a demand message to IPFS. The message fields are as follows:

- Field *model*: this field is an IPFS hash, which is the desired behavior model of a CPS. This model does not change during the tasks execution and uniquely identifies CPS.
- Field *objective*: IPFS hash pointing to a rosbag file containing ROS topics and dynamic parameters of the task.
- Field *token*: the address of the token to be used for payment.
- Field *cost*: the number of tokens.
- Field *lighthouse*: Lighthouse address.
- Field *validator*: Validator address.
- Field *validatorFee*: commission for Validator.
- Field *deadline*: number of the block in the distributed ledger, before the appearance of which the offer is relevant.
- The *sender* and *signature* fields identify the Promisee and are filled in automatically.

The message goes first to the Provider, and then to the CPS that is able to complete the task.If the CPS accepts, then it submits a response offer. Negotiations end when supply and demand messages are equal in the *model*, *objective*, *token*, *cost*, and *lighthouse* fields. In this case, a new Liability Contract is created in Ethereum.

The second stage — the Execution of the liability. An AIRA client waits for a message about the liability creation (*NewLiability()* event), analyzes the received fields and passes the information to the agent. The agent subscribes to the specified ROS topics to broadcast the necessary information, and then begins to perform the task. The AIRA client at this time reads the dynamic parameters and sends them to the agent.

After completing a task the Finalization stage begins. The agent notifies the client about the completion, the client collects the operation logs in the Result message, and then sends it to IPFS. If a Validator was specified, it first checks the results obtained. The Provider sees the notification about the results of the liability and then sends the transaction to Ethereum about its completion.

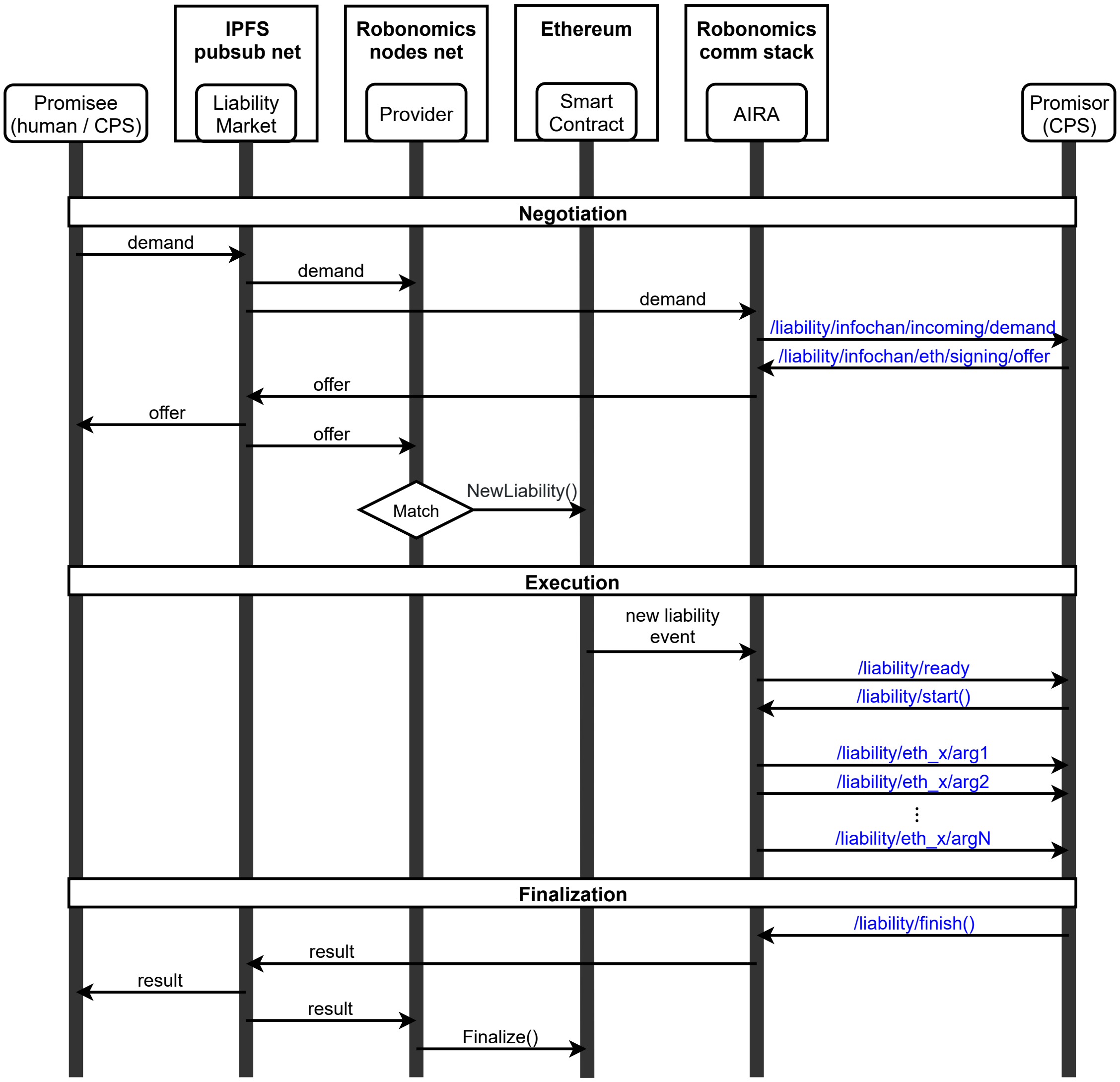

Fig. 1. The nodes communication scheme: the order of command execution is indicated from top to bottom, the blue font indicates information obtained from ROS topics.

V. Architecture of Unmanned Traffic Management

We have described the communication principles for nodes in Robonomics network. On this basis, we present a possible traffic management system architecture. In addition to the *Provider node* and the *Promisee node* referred to above, the following nodes are represented in the architecture.

Worker node. This is the cyber-physical system that does the work. It can be represented by an air, ground or water unmanned agent that can move and perform some of the required actions (for example, take a picture with a video camera or grab an object). When the Provider confirms the new commitment, the worker's node, via the installed

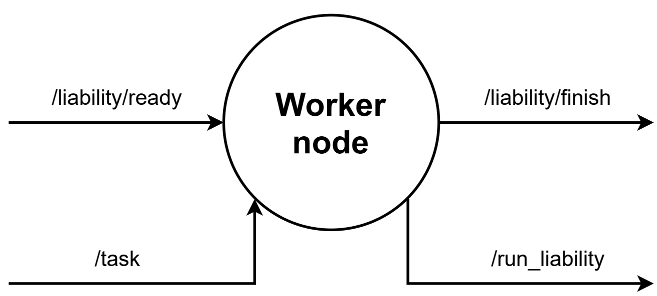

Fig. 2. Worker node and its topics.

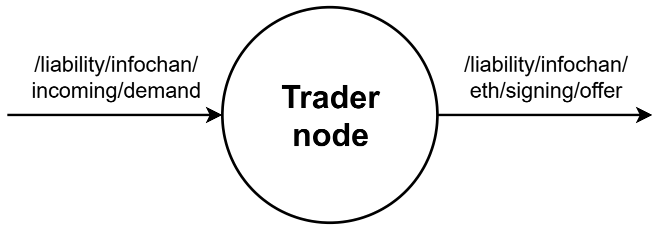

Fig. 3. Trader node and its topics.

AIRA Client, receives the behavior model and the addresses of the ROS topics. Through them, the agent must read the dynamic parameters to perform the work.

Trader node. This node is responsible for the economic behavior of CPS. Its main task is to monitor messages on the liability markets and select those that satisfy a) the CPS behaviour model, b) the programmed market node algorithms and the desired transaction parameters. In other words, this node is an economic agent from the CPS. At the same time, for each CPS, there can be a Trader node installed on the agent. Alternatively, one trader node, as a separate device, can be attached to several CPS, subject to work on the same model. It depends on the needs of the developer and the computing performance of the CPS.

The Trader's node, through its AIRA client, subscribes to Liability Markets messages and filters by selecting messages with the required model and parameters. If the message is found, the Trader does a supply offer. The decision to accept the obligation is made depending on a number of factors, for example: whether the CPS is free; whether the agent is able to move to a given point; are there any better offers, etc. Due to the existence of such nodes in the system design, you can use the algorithms of game theory, decision theory, economic theory, etc. [21].

Traffic Manager node. This is the main traffic control node. Its tasks are the following:

- checking for free agents and informing the trader about it;
- area map storage;
- plotting a route each time an agent is sent;
- tracking agents from starting point to arrival point.

In general, the developer of a traffic control system should solve each of the tasks, depending on the specific scenario of the agents. However, in our opinion the area map and the method of its storage must meet the following requirements:

- 3D model in which the free, occupied and unknown space is uniquely defined.
- Updatable maps: information from the agent sensors can be used to supplement the map, and the measurement noise must be taken into account.
- Dynamic map extensibility, with no predefined size.
- Efficiency in time when performing requests to the map and compact storage in the memory of nodes and CPS.

For the construction of optimal routes, researchers have developed a greater number of different algorithms. For example, one can cite short-path search algorithms (Dijkstra, Floyd, A *), random search algorithms (genetic, particle swarm optimization, ant colony optimization), etc. [22].

One way or another, as a result, the Manager will generate a set of points and start publishing them into the ROS topic for the agent who must follow them. Each time the agents position changes, the manager will check that the coordinates correspond to the route (along with some threshold caused by positioning errors). After the CPS completes its work, the Manager will send a *finalize()* message indicating the fulfillment of the liability. The work results will go to the network to Promisee and Provider.

VI. Proofs of Concept

Primarily the architecture was designed to be used with drones. This will allow you to request a mission to conduct measurements of air quality in a particular area. Software for the UI and map of the area was provided by our colleagues from Simlabs, Inc. A video demonstrating the work of all nodes is available here [23]. A detailed scheme of the system is shown in the figure 4.

The DJI Matrice 100 drone was chosen as an autonomous agent because it has an SDK with ROS support. The drone was equipped with a set of Libelium sensors and single-board Raspberry Pi 3 computer, which is responsible for storing data and transferring it to the network. The described nodes of the traffic management system were represented

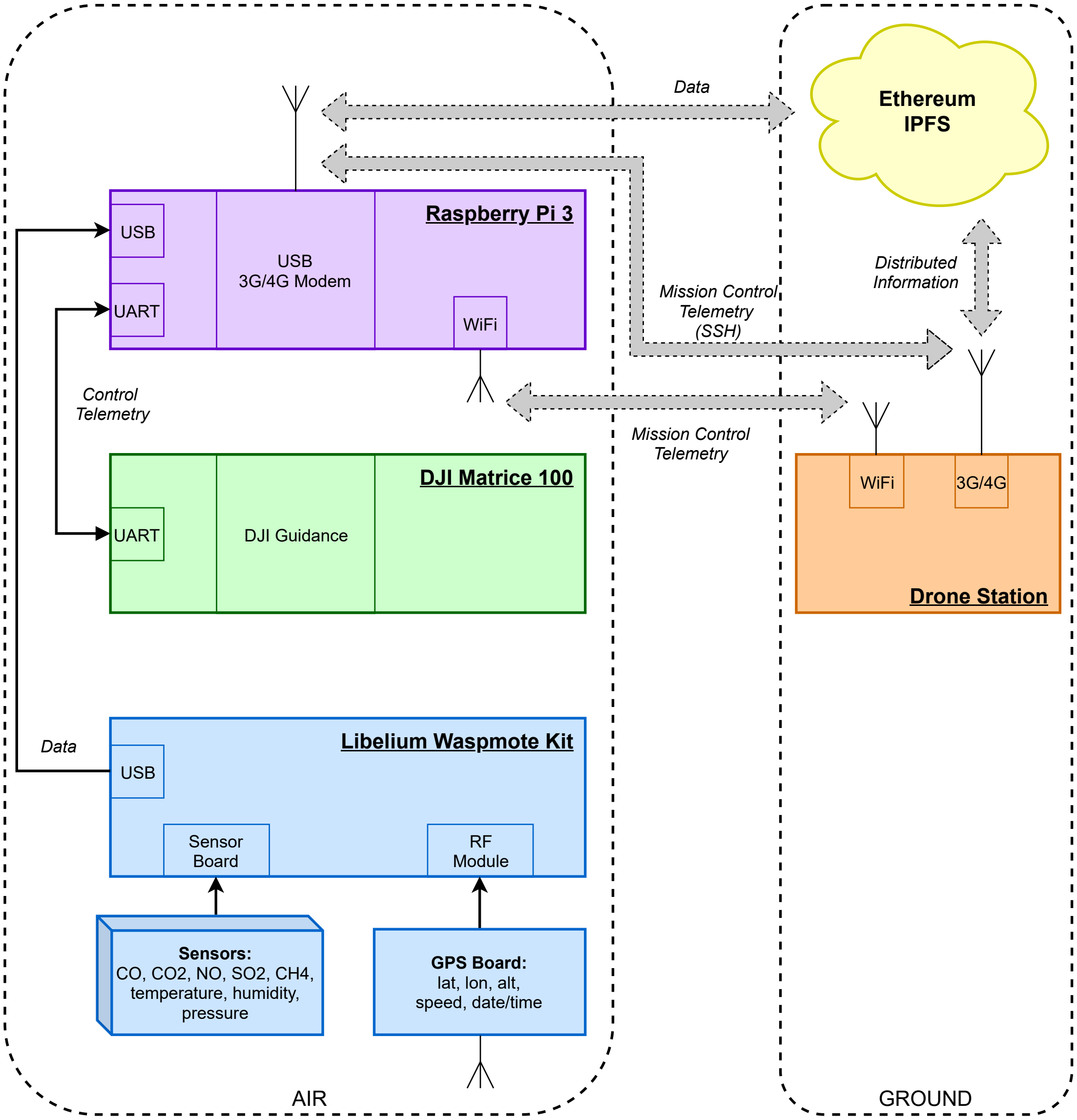

Fig. 4. System diagram for measuring air quality: solid black arrows is a direct connection of devices, gray dashed arrows — wireless connection.

by the Drone Station — a common laptop with the installed software. The station received a request from the user, then generated a mission and sent it to the drone. The growing area algorithm [24] was used for route planning.

Tests were conducted with an unmanned waterborne autonomous agent. A catamaran-type boat was designed and equipped with two propellers (max. speed 7 km / h), solar panels (200 W max) and a set of Libelium sensors for water analysis. Intel NUC was used as the computer, which had installed AIRA client for communication with the network and software for reading sensor data. The Pixhawk controller and the PX4 autopilot were used for navigation and motion control. The mission transfer and the route installation were similar to the tests with the drone.

According to the plan the USV was to measure a series of chemical indicators (pH, dissolved oxygen, electrical conductivity, etc.) in the reservoir. When the route was received the boat began to bypass the territory and stopped at each point necessary for measurements. The results of one of the measurements are shown in the figure 5.

In both experiments, the data received by autonomous agents is stored locally and transferred

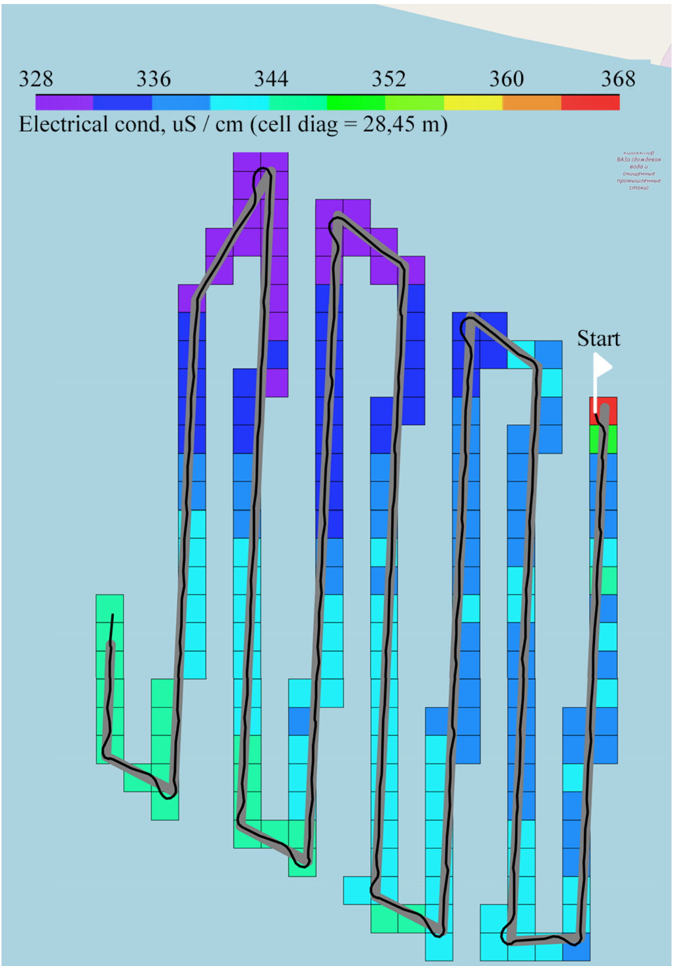

Fig. 5. The part of the map on which the results of water quality measurements are plotted: the black line shows the real path of the boat, the gray line shows the planned route of the mission, the colored cells show the averaged measurements of the electrical conductivity.

to the network for storage using IPFS.

VII. Conclusion

Let summarize our work and highlight the main points:

- We have presented one of the variants of the architecture of the control system for unmanned traffic based on the decentralized Robonomic protocol.
- We explained how this architecture meets most requirements for unmanned traffic management systems.
- We demonstrated evidence of this concept through two successful experiments: measuring air quality using a UAS and measuring water quality using a USV.

Results of the test allow us to apply our approach to building large traffic management systems. In further work, we will consider more complex experiments involving several autonomous agents of the various types. We will also simulate the work of many agents and explore optimizing traffic methods.

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