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DEPLOYMENT OF A UAV SWARM-BASED LiFi NETWORK IN THE OBSTACLE-RIDDEN ENVIRONMENT: ALGORITHMS OF FINDING THE PATH FOR UAV PLACEMENT

The subject *of this study is unmanned aerial vehicle (UAV)-based wireless networks in an obstacle-ridden environment.* ***The aim*** *of this study is to develop methods and software to ensure reliable LiFi communication using swarm UAVs in an obstacle-ridden environment.* ***The objectives*** *are as follows: 1) to describe the problem of providing a reliable UAV swarm-based LiFi network, requirements for the composition and use of UAVs, and assumptions; 2) to develop the methodology for solving research tasks; 3) to develop the method and algorithms for solving the problem, considering the requirements, assumptions, and practical limitations; 4) to explore the algorithms by developing software for modeling and searching for rational UAV placement to ensure the required UAV-based LiFi network characteristics; 5) to provide experiments and illustrative examples of the developed tool's application. The following* ***results*** *were obtained. 1) The requirements for the composition and use of UAVs for creating LiFi networks, as well as assumptions and limitations for the methodology development and research task solving. 2) An obstacle avoidance method using the left and right angles algorithm. 3) A method for obstacle avoidance using the controlled waterfall algorithm. 4) A software tool for modeling and searching for rational UAV placement to ensure the required LiFi network characteristics. The tool allows route construction under obstacles in 2D space and a comparison of the developed algorithms for various variants of obstacle placement.* ***Conclusions****. The main contribution of this research is a set of methods, algorithms, and software tools for providing communications between two points using LiFi technologies and a swarm of UAVs supporting these communications as transmitters in conditions of mechanical obstacles.*

Keywords: *unmanned aerial vehicle; UAV swarm; LiFi network; obstacle-ridden environment; obstacle avoidance algorithm.*

1. Introduction

1.1. Motivation

Because of hostilities caused by man-made and natural disasters, critical infrastructure facilities may suffer significant damage. Such facilities should have crisis centers to receive reliable and up-to-date information from the scene, such as the degree of destruction of process equipment, location of affected and potentially affected persons, and type and degree of contamination of the production environment and the surrounding area.

In addition to classical solutions, unmanned aerial systems can solve this problem for the following reasons:

Rapid response and on-site assessment. Unmanned aerial vehicles (UAVs) help rapidly deploy to the vicinity or site of an accident, which helps reduce response times and allows personnel to assess the extent and characteristics of the event, potentially saving time and reducing risk to humans.

Personnel safety. In hazardous environments, such as chemical, biological, or radiation contamination, UAVs equipped with cameras and other sensors allow remote assessment without endangering personnel.

Access to hard-to-reach areas. Critical infrastructure production facilities often have complex layouts, limited space, or tall structures that are difficult to reach in an emergency. UAVs can navigate such complex environments and provide access to areas that may be inaccessible or dangerous for humans. UAVs can collect visual data from various angles. This information can provide a comprehensive understanding of the accident.

Cost-effective solution. Compared with traditional methods during an accident, the use of UAVs can be a more cost-effective approach. This approach eliminates the need for a workforce, specialized equipment, and potential delays in establishing communication nodes. A UAV network can be deployed quickly, thereby reducing costs and editing time.

For such a problem, it is crucial to develop methods and algorithms for optimal planning of UAV-based systems according to information delivery time, reliability, and cost criteria.

Many tasks are associated with using different unmanned systems, including delivering goods to hard-to-reach places, flying over checkpoints and communication hubs, video surveillance, and sensor data collection, etc. In addition, unmanned systems can organize communication between crisis centers and victims (or points of information measurement). For this purpose, wireless (WiFi) and optical (LiFi) technologies are used considering the requirements of time and security limitations [1, 2]. Compared with WiFi, LiFi technologies have higher data transfer speeds, increased security, and resistance to electromagnetic interference. However, Wi-Fi technology may be less efficient and not suitable for use in critical infrastructures due to its greater susceptibility to electromagnetic interference, low bandwidth compared to LiFi, and possible data leakage during data transmission. LiFi technology is more resistant to these problems and offers the prospect of solving problems at critical infrastructure facilities. Therefore, the task of developing algorithms for delivering information despite destruction and interference is relevant.

1.2. State of the art

The operating conditions of critical infrastructure systems place strict limits on the requirements for UAV operation. First, the use of UAVs must not violate the safety and legal requirements of the country where the facility is located. For example, the author of [3] provides an overview of recent applications of UAVs for critical infrastructure inspection. The following advantages of using UAVs for critical infrastructure are highlighted:

- accessibility. UAVs can operate in conditions that are difficult for humans to access and inspect hard-to-reach places;
- efficiency. UAVs allow for the collection of data on large areas quickly;
- safety. The use of UAVs reduces the risk to employees performing inspections.

The author also highlights the following disadvantages of using UAVs:

- legislative restrictions. Mainly, there are requirements for the registration and certification of UAVs, and restrictions on the height and time of flight. For example, in the US, UK, and China, registration requirements exist if UAVs exceed 250 g and cannot fly further than 5 miles from an airport.
- safety. Inconsistent flight, especially at high altitudes, can be dangerous for other aircraft and people on the ground.
- technology. Currently, technological limitations are related to the parameters and duration of the flight. However, technology is developing, and the time and quality of flights are increasing.

The authors of the article conclude that the use of UAVs for critical infrastructure inspection has excellent potential, but further development of the technology is needed to ensure its safe and effective service [4, 5].

When developing diagnostic systems within critical infrastructure facilities, an important role is played by analyzing possible interference during UAV operation within the task. Interference can be different, directly affecting the UAV’s movement and signal interference. The author of [6] considers modern methods of counteraction in wireless sensor networks. According to the author, the use of UAVs in countering interference is as follows:

- mobility. UAVs can be moved anywhere in the wireless sensor network to provide coverage where traditional jamming methods are ineffective
- maneuverability. UAVs can maneuver around sources of interference to avoid impact.
- accessibility. UAVs are becoming more affordable and more accessible as technology advances.

The following methods for counteracting interference sources are proposed:

moving to the source of the interference. This method is based on actively suppressing interference during intentional and unintentional interference with the network. The UAV may have the means to neutralize interference on contact. This method can be effective in a targeted attack by intruders or interference from stationary sources. However, the technique also has disadvantages. For example, this solution may be expensive, or the UAV may not be able to neutralize the interference and will fail;

- creation of interference-resistant communication channels. A UAV may be equipped with hardware to transmit data in an interference environment. For example, a UAV can use signal modulation techniques resistant to interference or data encoding techniques to recover data damaged by interference. This method is more cost-effective and safer than using a UAV to travel to the source of the interference. However, it may also be less effective than the previously discussed method. It may also require more sophisticated equipment.
- data transmission using repeaters. UAVs can act as repeaters to avoid interference. In a node, a UAV can simultaneously be both a receiver and a transmitter. This method is more efficient than earlier methods but can reduce network capacity. It may also require more sophisticated UAV-based solutions capable of acting as repeaters.

Thus, considering the approaches and methods considered, it will be necessary to solve the problem in an interference environment, where it is proposed to use UAV-based repeaters with LiFi data transmission technology as a basis. The analysis showed that the method can be more effective, and LiFi technology will

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allow obtaining an interference-resistant channel with a high data rate.

The dynamic development of UAVs and LiFi technologies makes it possible to describe in detail the basic characteristics of UAVs necessary for solving the problem of signal transmission and shortcutting. Currently, there are sufficient materials that represent the use of UAVs in connection with LiFi technologies. For example, the authors of [7] analyze the Unified Physical Layer (UniPHY) performance based on neural networks for hybrid LiFi-WiFi networks using UAVs in indoor environments. Using flying UAVs as network nodes in hybrid LiFi/WiFi networks can provide several benefits, such as improved and higher quality of service, increased flexibility and deployment, and reduced interference and delays. However, the authors also identify possible challenges, such as dynamic changes in network topology and the need to ensure security and confidentiality. In turn, the authors of [8] present an overview of the use of software-defined networks (SDN) and network functions virtualization (NFV) for UAVs. SDN and NFV are technologies that make it possible to increase the flexibility, scalability, and manageability of networks. SDN separates the control plane from the data plane, allowing for the centralized management and programming of network behavior. NFV enables the virtualization of network functions, making them more flexible and scalable.

The paper [9] provides an overview of the use of UAVs to support network edge computing in Internet of Vehicle (IoV) 6G networks (VEC). The author notes that using UAVs to help VEC in IoV 6G networks has several advantages, such as reduced latency, increased performance, expanded network coverage, and increased communication reliability.

Thus, it can be noted that the use of UAVs is currently profitable, and many solutions based on UAV technologies are emerging.

Significant progress has been made in the field of LiFi recently. LiFi is a data distribution technology that transmits light pulses in the visible spectrum.

When reviewing the technology, the authors of [10] considered the application of LiFi technology for vehicle-to-vehicle (V2V) communication. LiFi has several advantages over traditional RF technologies, such as Wi-Fi and Bluetooth, including high bandwidth, security, and interference resistance. These advantages make LiFi an ideal technology for V2V communication, which can be used to improve road safety and increase transport efficiency. The authors of [11] discuss the progress made in improving the performance of LiFi systems, such as increasing throughput, range, and security. They also discuss the prospects for LiFi, such as its potential applications in 5G and beyond. The main point is that LiFi is a promising wireless data transmission technology with many advantages over radio frequency technologies. LiFi can be used in 5G, IoT, and cybersecurity applications. LiFi can revolutionize the wireless communications industry by providing higher bandwidth, security, and energy efficiency than traditional radio frequency technologies. However, the technology also has several limitations that need to be considered when choosing a technology for a specific task, such as limited range and the requirement for specialized equipment.

Combining possible data transmission technologies is also a relatively common area of research. The authors of [12] provide an overview of the state-of-the-art and critical research areas in the development of hybrid optical wireless networks. Note that hybrid networks combine the advantages of optical and radio wave communication, which makes it possible to overcome the limitations of each technology separately and provide higher throughput, reliability, and energy efficiency.

This study considers various combinations of hybrid systems, including RF/optical and optical/optical systems. The article notes that hybrid optical wireless networks are a promising solution to meet the growing demand for high-speed and reliable wireless communications.

Paper [13] deals with the security problems of the LiFi technology. The following possible attacks on the communication channel are considered:

- attacks on privacy: because LiFi uses visible light, it is possible to intercept data through the analysis of light fluctuations;
- attacks on data integrity: Attackers can alter LiFi data by manipulating the intensity or frequency of light oscillations;
- availability attacks: Attackers can block or disrupt LiFi data transmission by blocking or altering the light signal.

It also discusses various methods for securing LiFi, such as data encryption, authentication, and attack detection. In general, LiFi is a secure technology, but some security measures must be taken to protect LiFi data and networks from attacks, such as the following:

- data encryption can protect LiFi data from interception and further modification;
- authentication can help prevent unauthorized access to LiFi networks;
- development and implementation of attack detection systems that can detect and block attacks on LiFi networks.

The authors of [14] provide an overview of obstacle avoidance proposals and UAV architectures. Different approaches are generally considered, including sensor-based, planning-based, and control-based approaches. Various network architectures, such as peer-to-peer, centralized, and hybrid networks, are also discussed. The authors conclude that obstacle avoidance and network architecture are two of the most critical aspects of developing reliable and efficient UAVs. They note that there are many different approaches to obstacle avoidance and network architecture, and the choice of the appropriate approach depends on the specific UAV application.

In general, LiFi technology has excellent prospects for development in the foreseeable future and can be applied in various areas.

Recently, increasing attention has been paid to solving problems related to obstacle avoidance and path planning for ground and aerial robots. For example, the authors of [15] applied the Delaunay triangulation algorithm and the improved A* algorithm to analyze complex obstacles and generate Voronoi points as priority pathfinding nodes to enhance the efficiency of mobile robot trajectory planning. First, the authors build a triangular grid based on a set of obstacles and nodal points. The corner points are then constructed into a graph, which is used in the improved A* algorithm to find the shortest path between the start and endpoints. First, it should be noted that the algorithm is robust to changes and simple to implement. However, the algorithm may also be less efficient in simple environments, may lose efficiency in dynamic environments where changes occur quickly, and may be computationally expensive for large environments.

Study [16] presents a new approach to dynamic path planning for mobile robots based on a hybrid solution of ant colonies and dynamic windows. The ant colony algorithm (ACO) is a bio-inspired search algorithm that mimics the behavior of ants searching for food. The Dynamic Window Algorithm (DWA) is a real-time path planning algorithm that considers the robot's current state and dynamic changes in the environment. The proposed approach combines the advantages of ACO and DWA to create a more efficient and robust path-planning algorithm. ACO is used to find a global path to the goal, and DWA generates a local path that the robot can follow in real-time. The authors suggest possible algorithm applications such as warehouse navigation, autonomous driving, robot couriers, and robot scouts.

In [17], a method based on deep learning, a ray-tracing algorithm, an expectation rule, and a Rapid-exploring Random Tree is proposed. The proposed approach uses a neural network to train a model that can predict safe paths for indoor robots. The neural network is trained on a dataset consisting of images of the environment and information about obstacles. The authors consider the algorithm to be suitable for use in office navigation, hospital navigation, etc.

The article [18] describes a new approach to UAVs avoiding objects using the Floyd–Warshall differential evolution (FWDE) algorithm. FWDE is an evolutionary algorithm that uses the Floyd-Warshall algorithm to find the shortest paths between all pairs of points in a graph. The graph represents the environment in which the UAV must avoid obstacles. The approach works as follows. First, the environment graph is built using the UAV's sensors. The FWDE evolutionary algorithm is then used to find the shortest path from the current position of the UAV to the target, avoiding obstacles; the UAV follows the shortest path found by the evolutionary algorithm.

The study [19] considers the issue of designing a quadrotor trajectory in the shortest possible time through a series of defined waypoints, taking full advantage of the quadrotor dynamics. First, an environment graph is built using data from the quadcopter's sensors. Then, the A* algorithm is used to find the shortest path from the current position of the quadcopter to the target while avoiding obstacles. The quadcopter follows the shortest path found by A*.

To maximize the information collected by multi-copters during the inspection of large buildings, the paper [20] considers the problem of finding an approximately optimal path passing through a series of desired inspection points in a three-dimensional environment with obstacles. The proposed method comprises two stages: global path planning and local path planning. In global path planning, a rough path is planned from the start to the end to avoid obstacles. This is done using a graph-based path-planning method. In the local path planning stages, a more detailed path is planned, considering dynamic changes in the environment and the limitations of the multicopter. For this purpose, a potential field-based path-planning method is used.

Research is gaining momentum on the use of UAVs to provide LiFi connectivity indoors and outdoors. Study [21] presents the development of an interface protocol for a routing protocol unique to indoor flying ad hoc networks (FANETs) that use LiFi as a communication link. A FANET (Flying Ad-Hoc Network) is a network of UAVs that communicate without using base stations. FANETs can be used for various purposes, such as environmental monitoring, parcel delivery, and search and rescue. In [22], a drone-based weather monitoring system is considered, in which drones transmit the collected information to a ground station using LiFi technology.

To protect information and data in FANETs, [23] evaluated the feasibility of using LiFi with multiple UAVs for indoor collaboration and cooperative networks.

The authors of [24] provide an overview of research on obstacle avoidance for UAVs in indoor environments. They discuss various aspects of obstacle avoidance, such as obstacle detection methods, obstacle avoidance algorithms, challenges, and prospects. It is concluded that indoor obstacle avoidance for UAVs is challenging, but

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significant progress has been made in recent years. Further development of sensor modules, obstacle detection methods, and obstacle avoidance algorithms will make obstacle avoidance for UAVs in indoor environments more reliable and efficient.

The paper [25] proposes an approach to placing UAV repeaters in IoV networks and offers an approach based on evaluating possible solutions.

Thus, the analyzed papers provide an idea of the prospects of UAV and LiFi technologies and the direction of finding the shortest path and minimum distance. However, these papers exclude the issue of using path-planning methods to deploy LiFi networks in the presence of obstacles.

1.3. Objectives and the approach

This study aims to develop methods and software to ensure reliable LiFi communication using UAVs as repeaters in the event of mechanical interference caused by an emergency and destruction. It is necessary to develop a method for determining the priority path from point A to point B despite obstacles with the designation of coordinates for UAV placement. The communication line is a broken curve of the LiFi signal between the starting point, repeaters (if necessary), and the endpoint. During the development process, it is essential to consider the limitations and assumptions within the task. The developed algorithm should be evaluated with respect to the minimum distance travelled and the minimum number of UAVs deployed. It is necessary to propose improvements to the developed method, evaluate it using the same indicators, and consider the advantages and potential disadvantages.

The main objectives and stages of this research are as follows:

- stage 1. Describing the problem of providing a reliable UAV-based LiFi network, requirements for the composition and use of UAVs, as well as assumptions, and developing the methodology for solving research tasks (Section 2);
- stage 2. Developing a method and algorithms for solving the problem, considering the requirements, assumptions, and practical limitations (Section 3);
- stage 3. Exploring the algorithms by developing a software tool for modelling and searching for rational UAV placement to ensure the required UAV-based LiFi network characteristics (Subsection 4.1) and providing experiments and illustrative examples of the tool's application (Subsection 4.2);
- stage 4. Discussion of the results and formulation of recommendations (Section 5);
- stage 5. Briefly summarizing the results obtained and describing further research steps and development directions (Section 6).

2. Methodology

A basic algorithm was developed when developing a solution to the task, as shown in Fig. 1. The basic algorithm generally describes solving the job by presenting the main functional blocks as abstractions. However, some available blocks are considered in this article.

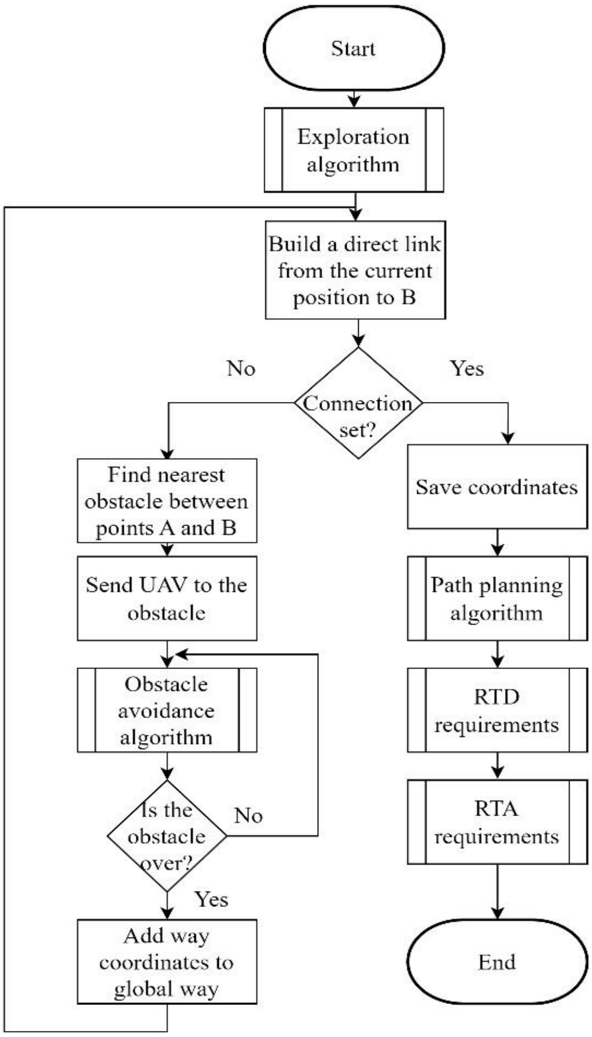

Fig. 1. General algorithm for solving the problem of establishing communication within an area with obstacles

The algorithm can be divided into several stages. The first stage involves exploring the working area to obtain information about the coordinates of obstacles and the boundaries of the active area. This stage is reflected in the "Exploration algorithm" block in the general algorithm. This block will not be considered in this article but will be the subject of further research. At this stage of work, we assume that we have enough data for the general algorithm to work.

The next step is to find a path from starting point A to ending point B. The general part is as follows: an attempt is made to connect the points in a straight line. If the connection cannot be built (there is an obstacle on the way), the algorithm evaluates the barrier. It uses the obstacle avoidance algorithm, represented by the "Obstacle avoidance algorithm" function block. This article considers this functional block as part of the construction of algorithms based on rectangle and controlled waterfall methods. The function block of the obstacle avoidance algorithm returns the path coordinates for the UAVs-repeaters to avoid the local obstacle, and an attempt is made to rebuild a direct link between the new obstacle avoidance point and end point B. Without a direct link, we repeat the steps of the "Obstacle avoidance algorithm" function block with updated data. The sequence of these steps is repeated until it is possible to establish a route along a given trajectory between A and B. If a direct connection has been established, then the function blocks of the "Path planning algorithm" are performed, and the requirements for the minimum distance between drones "RTD" and reliability requirements "RTA" are checked. The functional block "Path planning algorithm" will be considered in this paper. Thus, a general algorithm for solving the problem of establishing communication between the data point (point A) and the crisis center (point B) within an area with obstacles of arbitrary shape is presented. The following sections provide details on obstacle avoidance and flight planning algorithms.

3. UAV routing methods using LiFi in an obstacle-ridden environment

3.1. Obstacle avoidance method using the left and right angles algorithm

The development of the left and right angles algorithm aims to find the optimal path and establish a lifeline through repeaters between starting point A and end point B within the working area with obstacles [26].

In a simplified version, the task is described as follows: it is necessary to lay a communication line (route) from point A, which is the source of information, to point B, which the information user represents (or crisis center) on a static working area of arbitrary shape in 2D space, taking into account possible obstacles. Obstacles can take no form and be located within the workspace. Obstacles must be avoided by straight lines that form the general route. Figure 2 shows an illustrative example. A route is built from point A to point B according to the selected rule. This example shows the possible ways and the trajectories they create. The working area and obstacles are rectangular for simplicity. When deploying a communication system using UAVs to organize data transmission, it is necessary to consider the requirements for non-functional characteristics of the system and the corresponding limitations, such as the following:

- restrictions on the quality data transmission distance (RTD) for LiFi repeaters onboard UAVs. To ensure high-quality data transmission, the distance between neighboring UAVs must be less than the RTD value;
- the reliability value of the UAV during deployment and use should be greater than the required RDA;
- UAV reliability during deployment and use (RDA) should be greater than the required RDAreq.

Given these requirements, UAVs can be augmented with UAVs. Additional UAVs are shown as dashed lines in Figure 2 to illustrate the limitations of RTDs.

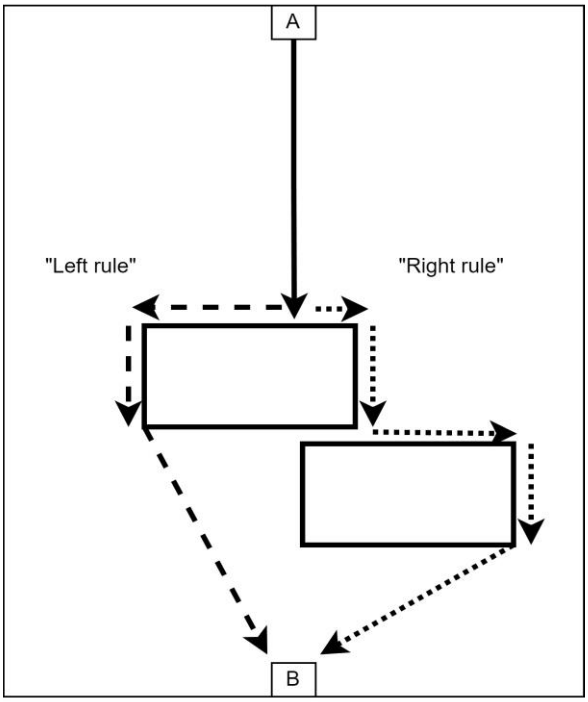

Fig. 2. An illustrative example of a rectangle method algorithm with execution steps

Thus, it is necessary to find the type of UAV in the values of RDA and RTD that were acceptable for solving the problem.

When developing a controlled waterfall algorithm, the following assumptions are made:

- time characteristics for the algorithm are not considered;
- UAV positioning algorithms to a point are not considered in this method but will be described as part of the development of positioning algorithms for UAVs;
- the total number of UAVs is sufficient for the task;
- all UAVs have the same characteristics (reliability, autonomy, data transmission distance);

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- the battery life is sufficient for the task at hand.

The illustrative examples show obstacles in the form of rectangles. However, the shape of the barriers can generally be described as a convex polygon. Blocks of any shape can be inscribed in a polygon of this shape.

In summary, we can state that the approach to solving the problem includes:

- analysis of strategies and selection of rational strategies for UAV deployment tasks;
- development of a method and algorithms based on the search for UAV routes (placement) using the principle of polygons;

correction of communication based on RDA and RTD.

When developing the obstacle avoidance algorithm using the rectangle method, the following requirements were identified:

- the problem is considered in 2D space, where each point is represented as (xi,yi);
- the working area during algorithm execution is constant;
- obstacles located in the workspace do not change their shape or coordinates over time; starting point A and ending point B are constant and do not change their positions over time;
- the characteristics and number of UAVs are sufficient for the task at hand;
- the task requires meeting the requirements of distance, effective communication, and reliability.

The solution of the algorithm is a sample of point coordinates that will be used to build the optimal path using UAV positioning algorithms. Currently, the rectangle solution provides a way to the endpoint that is not the most optimal but is a basic solution to the problem of finding the optimal path with the possibility of scaling and improvement.

The development of a path avoidance algorithm using the rectangle method is based on the considered strategies. Based on the results of the review, three strategies for constructing an obstacle avoidance algorithm using the rectangle method were identified, which we will conventionally denote as C1, C2, and C3;

- C1 – is a strategy for building an algorithm based on sequentially moving straight to a given point and bypassing the obstacle in a straight line. This strategy is characterized by the simplicity of the algorithm implementation and its effectiveness on a path with simple obstacles with straight edges around the perimeter. However, this algorithm may be ineffective in the presence of obstacles of arbitrary and complex shape;
- C2 – is a strategy for constructing a basic algorithm based on laying a route along a broken line with the definition of the next obstacle. This strategy does not have the main disadvantage of C1 because the movement is built for obstacles, avoiding the likely suboptimal paths of C1;
- C3 – a strategy for building a basic algorithm based on finding free space for route construction. This strategy allows flexible route planning depending on the conditions and required characteristics. However, when working with large-scale grids and large datasets, search algorithms can be computationally complex and take longer than C1 or C2.

When building the obstacle avoidance algorithm, it was decided to focus on the C2 strategy as the optimal one under the given conditions and goals. An obstacle avoidance algorithm was built using the rectangle method on the basis of the considered strategies. Figure 3 shows the implementation in the form of a block diagram. The implemented algorithm is a component of the basic algorithm shown in Figure 1 and replaces the "Obstacle avoidance algorithm" subroutine. The algorithm takes the coordinates of the start point, endpoint, and obstacles located within the working area as input.

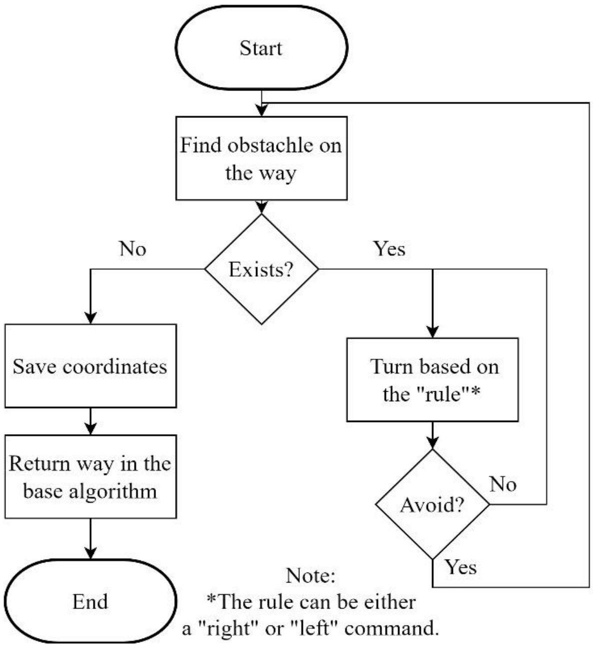

Fig. 3. Obstacle avoidance algorithm using the rectangle method

The Rectangular Obstacle Avoidance algorithm aims to find an obstacle between the start and end points and overcome the obstacle according to a predefined rule. This rule may be to turn left or right, looking for a closer angle to avoid the obstacle. Recalling the thesis that every obstacle of any shape can be inscribed in a convex polygon, this algorithm allows the avoidance of obstacles of any shape. The algorithm does not guarantee the optimal path, but it will enable the use of the solution as a base for improving the method and for further research.

3.2. Method for obstacle avoidance using controlled waterfall algorithm

The purpose of developing the controlled waterfall and rectangle algorithms is to find the optimal path and establish a lifeline through repeaters between starting point A and end point B within the working area with obstacles. However, it is also necessary to improve the algorithm to improve the values of the minimum distance travelled and the minimum number of UAVs deployed on the route [27].

In a simplified version, the task is described as follows: it is necessary to lay a communication line (route) from point A, which is the source of information, to point B, which the information user represents (or crisis center) on a static working area of arbitrary shape in 2D space, taking into account possible obstacles. Obstacles can take no form and be located within the workspace. Obstacles must be avoided by straight lines that form the general route. Figure 4 shows an illustrative example. STEP 1 shows an example of building all possible ways, and STEP 2 demonstrates the search for the shortest route based on the data obtained in STEP 1. When deploying a communication system using UAVs for data transmission, it is necessary to consider the requirements for non-functional characteristics of the system and the corresponding limitations, such as:

- restrictions on the quality data transmission distance (RTD) for LiFi repeaters onboard UAVs. To ensure high-quality data transmission, the distance between neighboring UAVs must be less than the RTD value;
- the reliability value of the UAV during deployment and use should be greater than the required RDA;
- UAV reliability during deployment and use (RDA) should be greater than the required RDAreq.

Given these requirements, UAVs can be augmented with UAVs. Additional UAVs are shown as dashed lines in Figure 4 to illustrate the limitations of RTDs.

Thus, it is necessary to determine the type of UAV and the values of RDA and RTD that are acceptable for solving the problem.

When developing a controlled waterfall algorithm, the following assumptions are made:

- time characteristics for the algorithm are not considered;
- UAV positioning algorithms to a point are not considered in this method but will be described as part of the development of positioning algorithms for UAVs;
- the total number of UAVs is sufficient for the task;
- all UAVs have the same characteristics (reliability, autonomy, and data transmission distance);
- the battery life is sufficient for the task at hand.

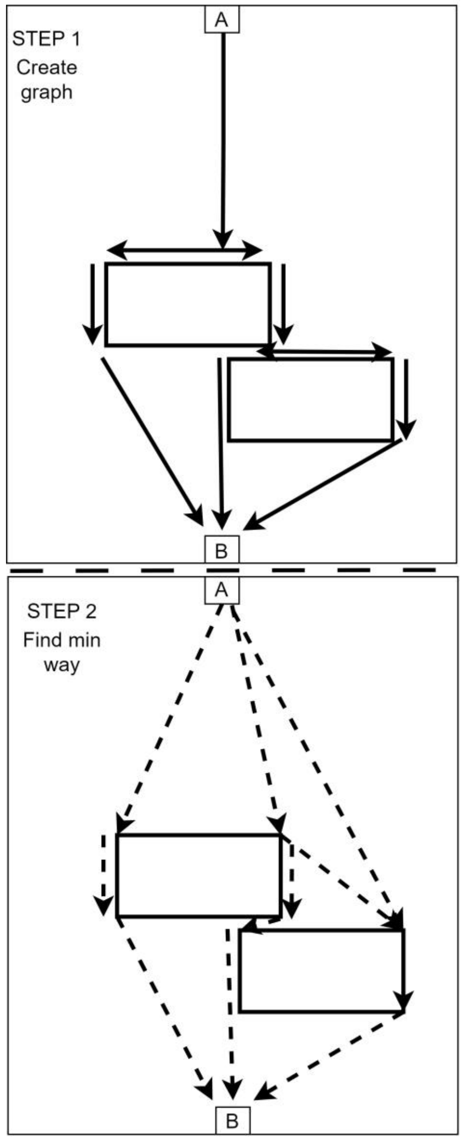

Fig. 4. An illustrative example of the controlled waterfall algorithm with execution steps

The guided waterfall algorithm is based on the rectangle method. It improves its performance regarding the minimum distance traveled and the minimum number of drones deployed.

The illustrative examples show obstacles in the form of rectangles. However, the shape of barriers can generally be described as a convex polygon. Obstacles of any shape can be inscribed in a polygon of this shape.

To sum up, we can state that the approach to solving the problem includes:

- analysis of strategies and selection of the most efficient one for UAV deployment;
- development of a method and algorithms based on the search for UAV routes (placement) using the principle of polygons;
- correction of communication-based on RDA and RTD;

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When developing the obstacle avoidance algorithm using the rectangle method, the following requirements were identified:

- the problem is considered in two-dimensional space, where each point is represented as (xi, yi);
- the working area during the algorithm execution is constant;
- obstacles located in the workspace do not change their shape and coordinates over time; the start point A and endpoint B are constant and do not change their positions over time;
- the characteristics and number of UAVs are sufficient for the task at hand;
- the task requires meeting the requirements of distance, effective communication, and reliability.

The solution of the algorithm is a sample of point coordinates that will be used to build the optimal path using UAV positioning algorithms. Currently, the rectangle solution provides a way to the endpoint that could be more optimal but is a basic solution to the problem of finding the optimal path with the possibility of scaling and improvement.

The guided waterfall algorithm is a complex solution that guarantees the improvement of the recommended waterfall algorithm with respect to the minimum number of UAVs placed on the route and the minimum distance travelled from point A to point B. Figure 5 shows the implementation of the guided waterfall algorithm.

The execution of the controlled waterfall algorithm consists of 2 parts. The first step is to search for all possible paths and build a graph. This block is based on the rectangle obstacle avoidance method, in which the rule for avoiding an obstacle is to turn left and right simultaneously. In other words, when a block is found between points A and B, it is necessary to prevent it from all possible sides while maintaining the coordinates of the obstacle corners and the coordinates of the potential first collision of the UAV on the tracking path.

After finding all possible ways according to this rule, the coordinates of the obstacle corners not included in the route are added to the coordinates. This decision is not mandatory and can be adjusted on the basis of requirements, but expanding the obtained coordinates with the angles of additional obstacles provides more variability in subsequent stages.

After all coordinate points are obtained, a path graph is built, from which edges that pass or cross obstacles are excluded. The second part uses the shortest path search algorithm. The resulting graph must be processed using the shortest-path search algorithm. In this study, we use the Dijkstra algorithm. The path found by the Dijkstra algorithm is returned as a value to the basic algorithm for solving the problem. This algorithm improves the efficiency of the obstacle avoidance algorithm using the rectangle method in terms of the minimum number of drones on the path and the minimum distance traveled; however, it requires more computing power.

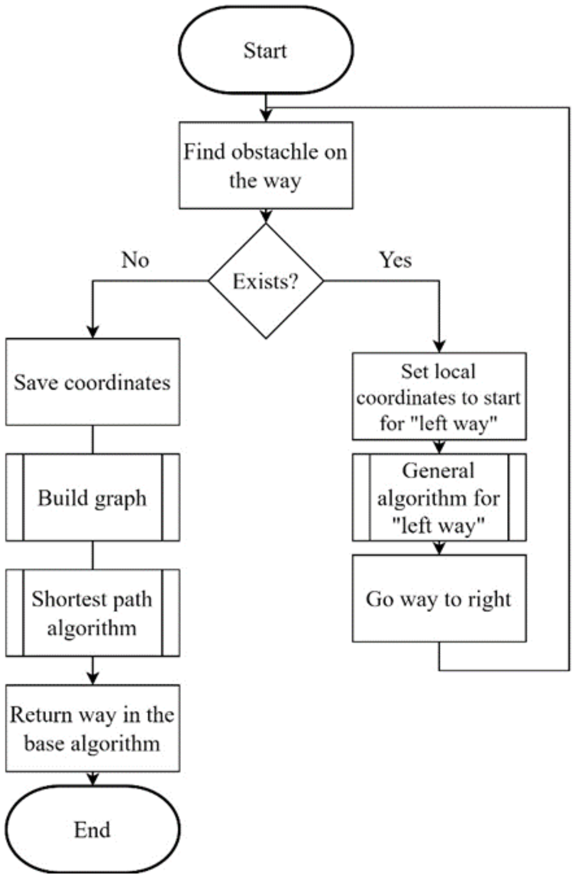

Fig. 5. Obstacle avoidance algorithm using controlled waterfall method

The process of executing the controlled waterfall algorithm can be displayed using the Simulation Way software tool, the structure and functionality of which are described in detail in Section 3. Let’s simulate a situation (Figure 6) where it is necessary to establish communication within a 20x20 working area with four obstacles that have dimensions of 5x5. The rectangle labelled A indicates the initial signal output point, and the rectangle labelled B shows the end of the signal input. The rectangular shapes indicate the 5x5 obstacles.

During the first step of the guided waterfall algorithm, possible obstacle avoidance points between the start and end points are obtained. A path graph is built on the basis of the data obtained, as shown in Figure 7.

The resulting graph is a set of possible vertices through which the UAV can move as part of the task. The vertices 0 and 9 are the start and end vertices of the graph, respectively. The vertex number reflects the order in which the point is added to the path array. Vertices 1, 6, 3, 7, and 8 represent the vertices of the route between the start and end points. The edges between the vertices have a value representing the distance between the vertices. The result is shown in Figure 8. The vertex number corresponds to the order in which the point coordinates are added to the point array.

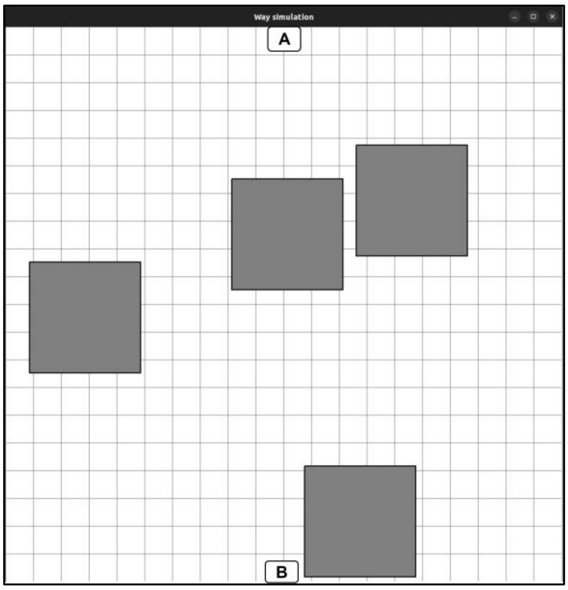

Fig. 6. Task within the "Simulation Way" software tool

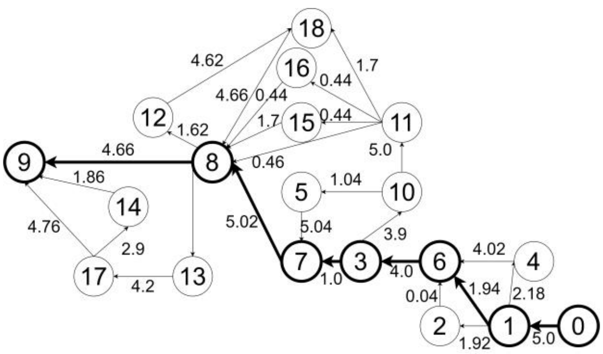

Fig. 7. A path graph that is built on the basis of the data obtained via the "Simulation Way" software tool

The broken line with points represents the path within the simulation software. This path reflects the results presented in Figure 7. Thus, 5 UAVs between the start and end points would be sufficient for this example.

4. Research on algorithms

4.1. Software tool description

The software tool is a comprehensive solution for the analytical crisis center for research and modelling of the developed algorithms. The software tool is written in Python and has the structure shown in Figure 9.

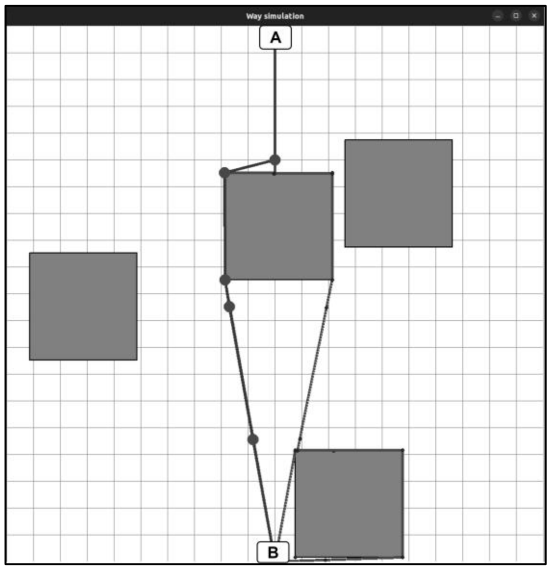

Fig. 8. Results of the task in the "Simulation Way" software tool

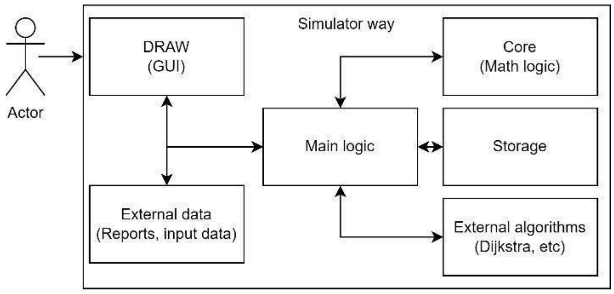

Fig. 9. Structure of the "Simulation Way" software tool

In studying the developed obstacle avoidance algorithms based on the rectangle and controlled waterfall methods, the basic tool is the developed Python application "Simulation Way." This software simulates UAV operation under specified conditions and is described in this subsection.

The basic components of a software tool are modules. "Draw (GUI)" is the interface of the software tool. "External data is a module for generating reports and statistics. "Storage" is the storage of the software tool's internal data. The "Core" module represents the mathematical logic of the project. "External algorithms" are external algorithms built for use in the project. The "Main logic" module is responsible for the interaction between the component modules and sets the basic logical framework of the software tool.

The software generates a rectangular working area according to the specified parameters and obstacles of arbitrary shape according to the specified parameters in a limited number. The main task is to find a path from point A to point B according to the given rules. The program interface is shown in Figure 10.

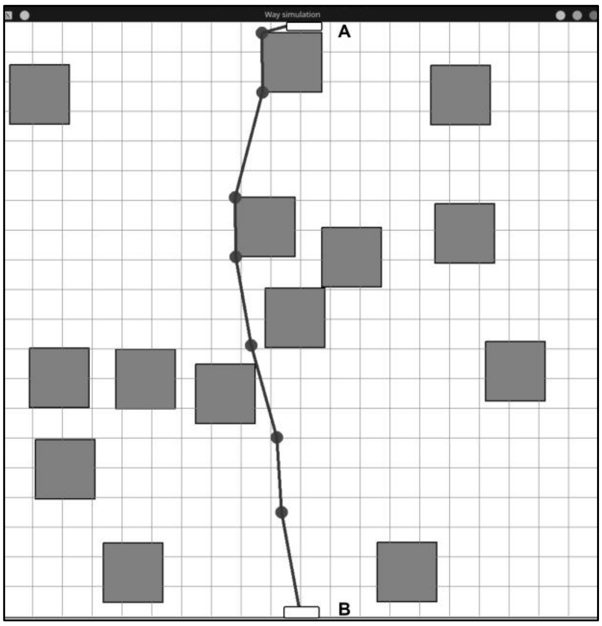

Fig. 10. Implementation of the controlled waterfall method using the "Simulation Way" software tool

In this example, the broken line represents the constructed path using the guided waterfall method, and the points on the line are the UAV locations along the path. The app allows turning off and on surfaces such as the marking grid, obstacles, distance travelled and placement locations for convenience.

The software is managed using the "Control" control window, as shown in Figure 11.

The application interface is a control panel for investigating the shortest path-finding tasks under obstacles. The primary purpose of the interface is to provide an environment for performing obstacle avoidance tasks for a fleet of UAVs.

The "Start" button executes the algorithm according to the specified parameters. The "Clear" button will clear the current plan and generate new obstacles according to the specified parameters. The "Dijkstra" button implements the Dijkstra algorithm within the Controlled Waterflow algorithm. The application can automate two types of experiments, where the value of obstacle parameters changes (experiment 1) or the parameters of the working area change (experiment 2). The field with the number of obstacles, length, and width allows for setting the challenges for the current experiment. "set_UAV" is a placement algorithm for UAVs that can use approaches to find the shortest path and positions for UAVs. In addition, the control panel has some inactive features that will be implemented in the next version, which currently represent alpha testing functionality.

4.2. Metrics

The indicators of the rectangle method/guided waterfall method efficiency experiment will be the study of the minimum number of UAVs placed on the path and the minimum distance covered when sampling from 1 obstacle on an area of 30 (or 45.5% of the working area coverage by obstacles with the maximum number of simultaneously placed objects) attempts and changing the following parameters within a series of attempts:

– number of 2x2 obstacles with a static working area of 20x20;

– number of 2x3 obstacles with a static working area of 20x20;

– number of 3x2 obstacles with a static working area of 20x20;

– a 20x20 working area with a constant number of 30 obstacles with 2x2 dimensions.

4.3. Experiments

The purpose of this experiment is to evaluate the effectiveness of the developed algorithms based on rectangles and controlled waterfall methods and to find dependencies between:

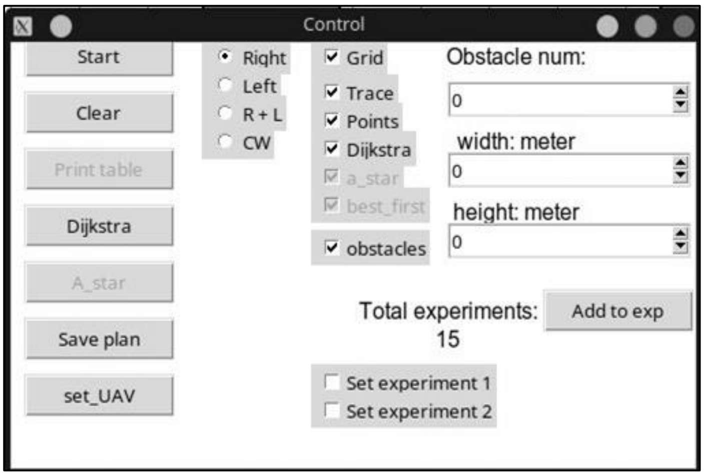

Fig. 11. User interface of the "Simulation way" software

- the change in the number of obstacles of the same size and the number of UAVs required to be deployed on the route;
- the change in the number of obstacles of the same size and minimum required distance;
- the change in the working area with a constant number of obstacles and the number of UAVs required to be deployed on the route;
- changing the parameters of the working area while maintaining the same number of obstacles and minimum detour distance.

Based on the input data, a group of experiments with the same 20x20 (400 m2) meters working area was conducted.

Between 1 and 30 obstacles were placed at random coordinates in the workspace area, with a size of 2x2 m (4 m2, maximum percentage of obstacle coverage = 29%) for experiment 1, 3x2 (6 m2, maximum percentage of obstacle coverage = 43.50%) for experiment 2, and 2x3 m (6 m2, maximum rate of obstacle coverage = 43.50%) for experiment 3.

The goal is to study and compare the effectiveness of the algorithms with a gradual increase in the number of obstacles in the path with a step of 1 in terms of the minimum number of drones on the path and the minimum required distance.

Experiment 1 demonstrates the dependence of the minimum required number of UAVs on the path (Figure 12) and the minimum required distance (Figure 13) in a 20x20 m area when the number of obstacles of 2x2 m size is changed from 1 to 30. The results of the experiment are shown in Figure 12.

The experiment results with the size of obstacles show that the guided waterfall algorithm showed the best values regarding the minimum number of UAVs placed on the path and the best result for most test sets regarding the minimum required distance covered. In addition, the left and right corner algorithms demonstrate values close to the guided waterfall algorithm. However, when the area is filled with obstacles by more than 14%, they may not proportionally increase the required values of the number of UAVs and the distance of the path. This is because of the basic rules of turning "left" or "right" without preliminary analysis. That is, the algorithm allows one to avoid an obstacle on the way in direct contact but does not change the rules during preliminary analysis, as the guided waterfall algorithm does in the first stage.

Experiment 2 demonstrates the dependence of the minimum required number of UAVs on the path (Figure 14) and the minimum required distance (Figure 15) in a 20x20 m area when the number of obstacles of 2x3 m in size varies from 1 to 30. The results of the experiment are shown in Figure 14.

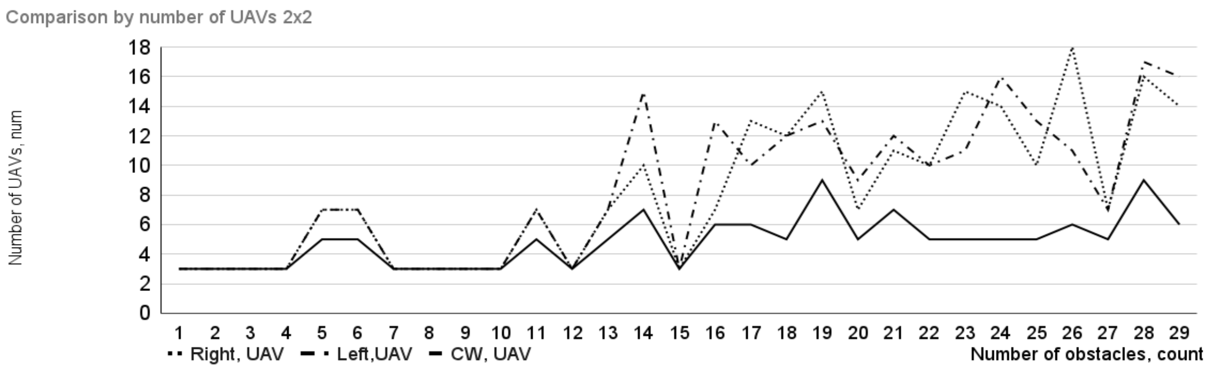

Fig. 12. Diagram of the dependence of the number of UAVs placed on the path on the change in the number of 2x2 obstacles in the working area

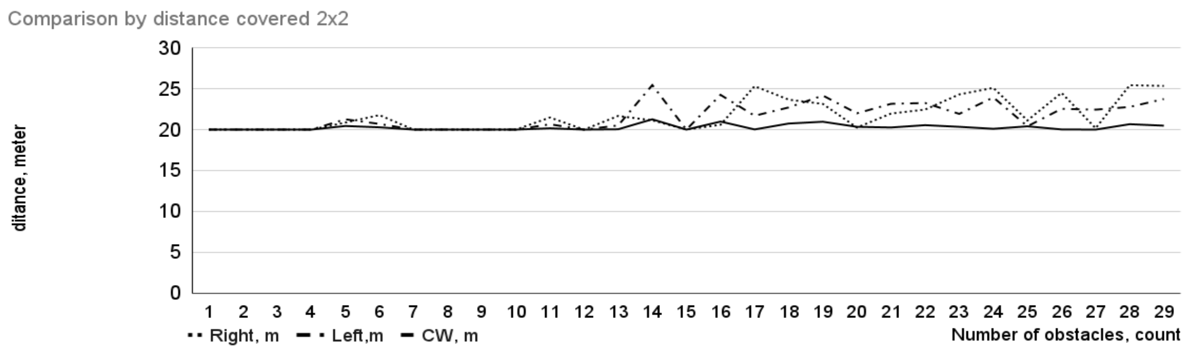

Fig. 13. Diagram of the dependence of the minimum distance travelled on the change in the number of 2x2 obstacles in the working area

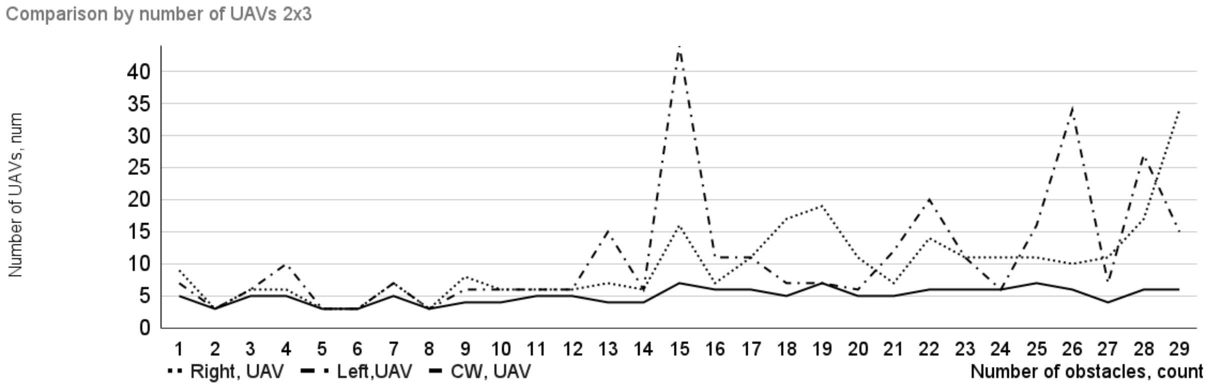

Fig. 14. Diagram of the dependence of the number of UAVs placed on the path on the change in the number of 2×3 obstacles in the working area

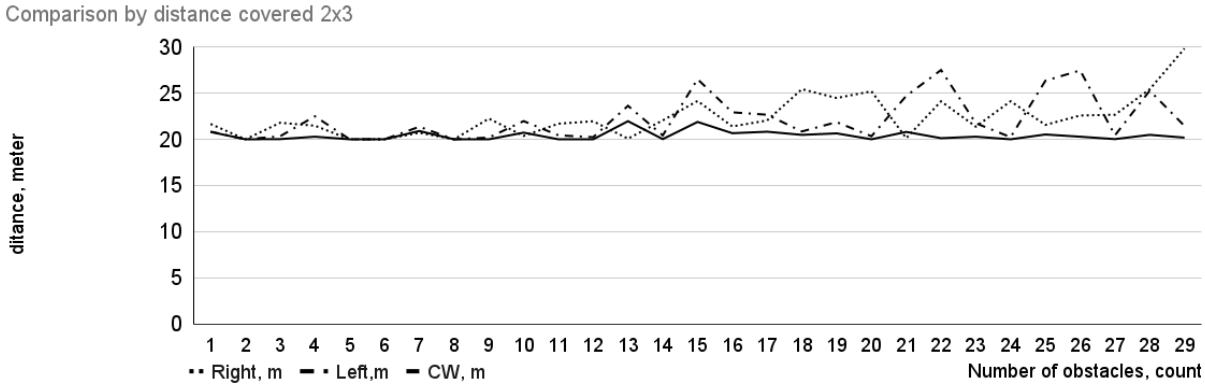

Fig. 15. Diagram of the dependence of the minimum distance travelled on the change in the number of 2×3 obstacles in the working area

The experimental results have features in common with Experiment 1; the controlled waterfall algorithm showed the best values for the minimum number of stirred UAVs on the path and the best outcome for most test sets regarding the minimum required distance travelled. Changing the area of the obstacle, where the block was stretched vertically by 1 m, did not dramatically change the results of the controlled waterfall algorithm but significantly affected the performance of some test results of the rectangle method algorithms regarding the minimum number of drones on the path. This result can be explained by the fact that as the obstacle length increases, it is necessary to use more UAVs for algorithms that avoid impediments at corners while limiting the distance between UAVs.

Experiment 3 demonstrates the dependence of the minimum required number of UAVs on the path (Figure 16) and the minimum required distance (Figure 17) in a 20x20 m area when the number of obstacles with 3x2 m dimensions varies from 1 to 30. The results of the experiment are shown in Figure 16.

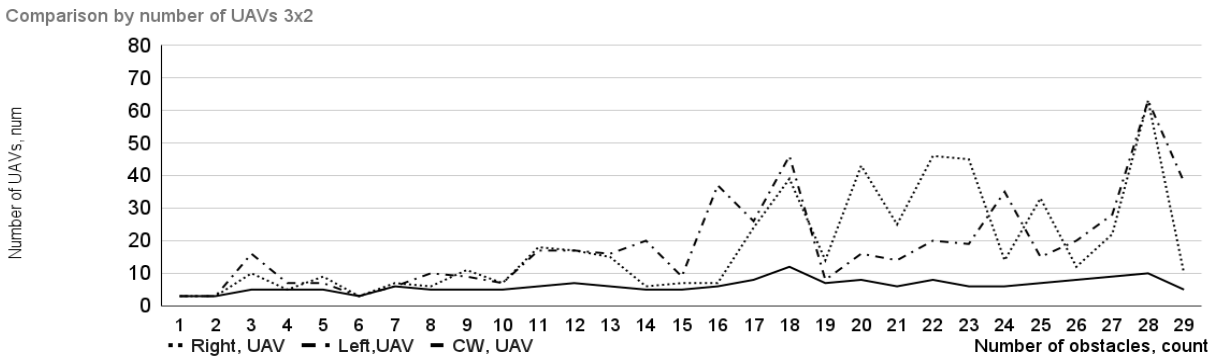

Fig. 16. Diagram of the dependence of the number of UAVs placed on the path on the change in the number of 2×3 obstacles in the working area

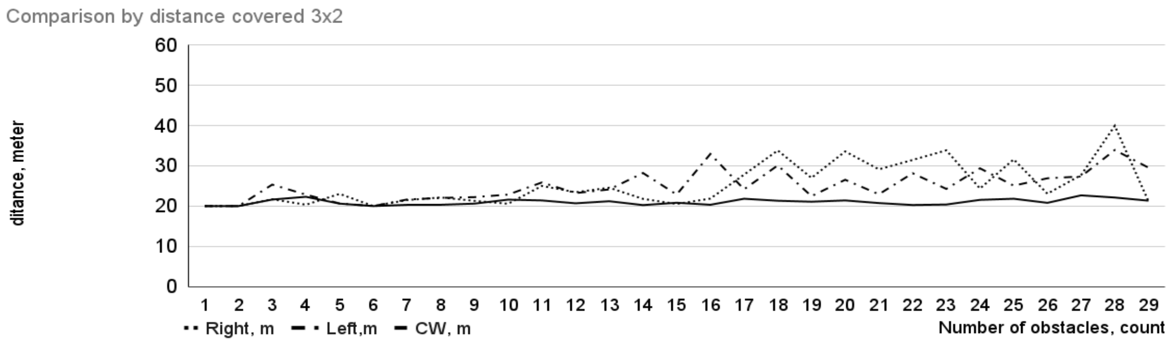

Fig. 17. Diagram of the dependence of the minimum distance travelled on change in the number of 2×3 obstacles in the working area

Analyzing the results of experiment 3, it can be noted that the guided waterfall algorithm performed best with respect to the minimum number of UAVs placed on the path and the best development in most test sets with respect to the minimum required distance travelled. However, it should be noted that as the width of the obstacle increased, the rectangle-based algorithms increased the values of the indicators in 14 test sets, unlike the guided waterfall algorithm. This result can be explained by the fact that as the obstacle length increases, it is necessary to use more UAVs for algorithms that avoid impediments at corners while limiting the distance between UAVs.

In addition, the results for the minimum number of UAVs and the minimum distance covered were plotted in graphs showing the dependence of the change in the algorithms' performance on the size of obstacles. The results for the correct corner algorithm are shown in Figure 18.

Analyzing the results of Figure 18, it can be concluded that when the set of obstacles has an increased width compared to the length (3x2), the suitable corner algorithm shows higher values regarding UAV placement on the path. This is because when the obstacle's width increases, the working space's coverage area between points A and B increases; therefore, the algorithm needs to avoid more obstacles.

Analyzing the results of Figure 19, we can conclude that when the set of obstacles has an increased width compared to the length (3x2), the suitable corner algorithm shows higher values for the minimum distance travelled. This is because as the obstacle's width increases, the working area's coverage area between points A and B increases, so the algorithm needs to avoid more obstacles.

The algorithm's results presented in Figure 20 are identical to those in Figure 21 and express the same dependencies given above.

The algorithm results presented in Figure 20 express the same usefulness as those in Figure 21.

Figures 22 and 23 show the results for the controlled waterfall algorithm when obstacle sizes are varied. Based on the results shown in Figures 22 and 23, we can conclude that when the width of the obstacle increases, the controlled waterfall algorithm finds solutions with values of the indicators that are higher than when the block remains the same and the height increases. This result can be explained by the fact that the algorithm should find solutions with more obstacles on the path that directly block the connection between A and B.

Experiment 4 demonstrates the relationship between the change in the working area (decreasing the width of the working area), the number of UAVs deployed (Figure 24) on the path, and the minimum distance travelled (Figure 25) for the right angle, left angle, and guided waterfall algorithms.

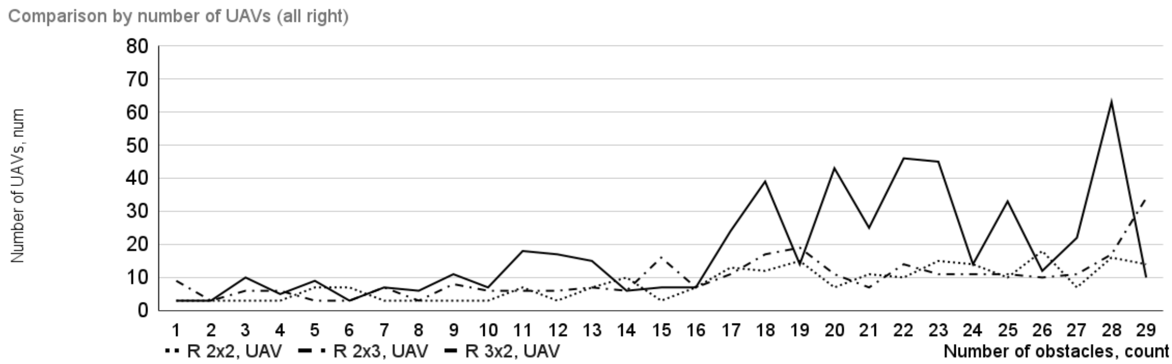

Fig. 18. Diagram of the dependence of the number of UAVs placed on the path for the correct corner algorithm based on the change in the size of obstacles

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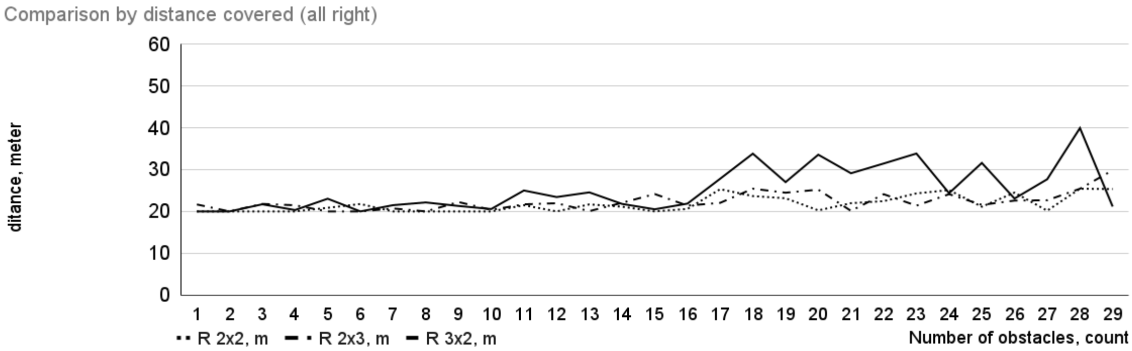

Fig. 19. Diagram of the dependence of the minimum distance travelled for the correct angle algorithm for the change in the size of obstacles

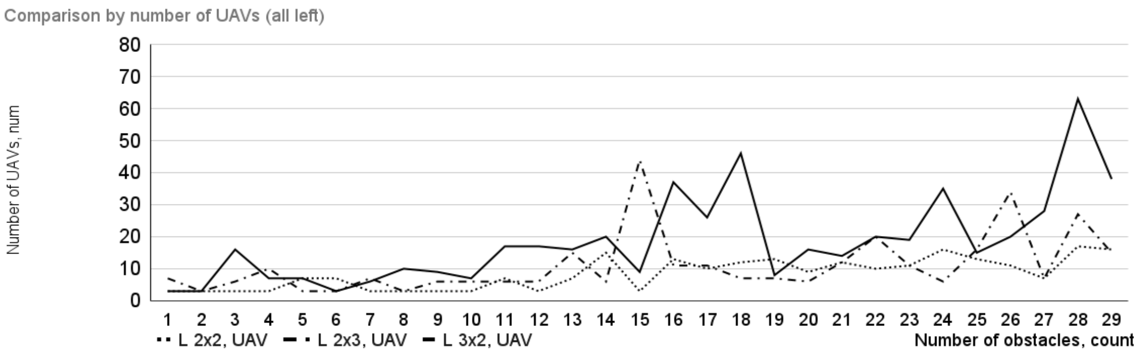

Fig. 20. Diagram of the dependence of the number of UAVs placed on the path for the left corner algorithm on the change in the size of obstacles

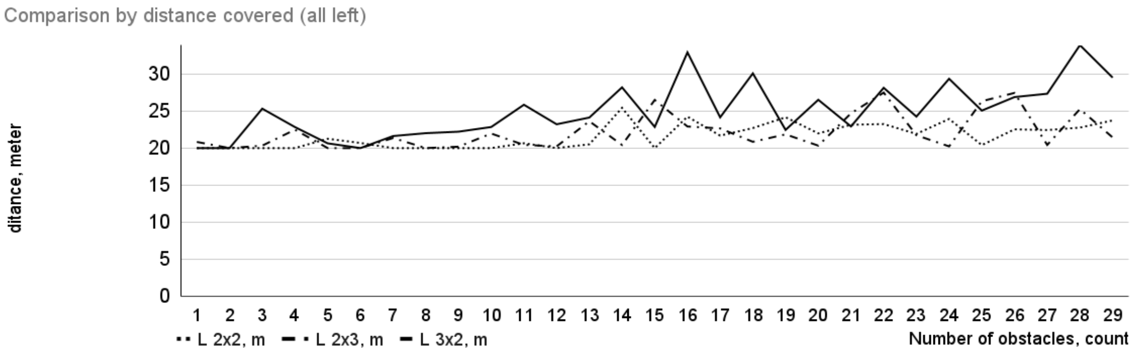

Fig. 21. Diagram of the dependence of the minimum distance travelled for the right-left algorithm on the change in the size of obstacles

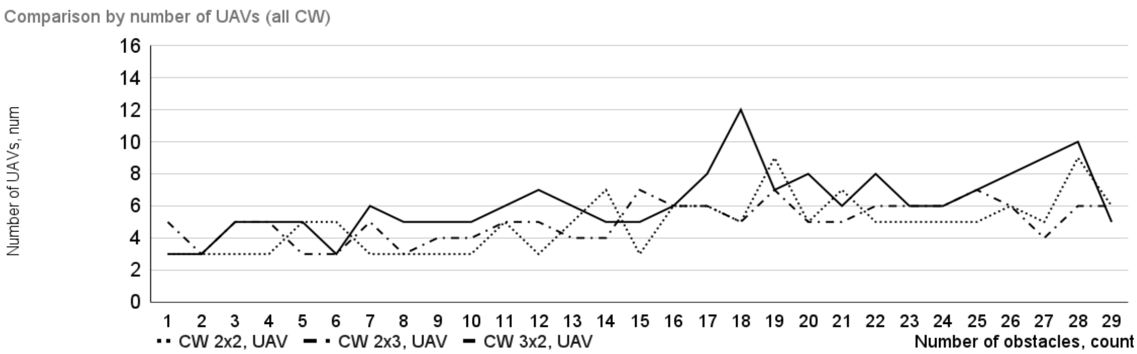

Fig. 22. Diagram of the dependence of the number of UAVs placed on the path for the guided waterfall algorithm based on the change in the size of obstacles

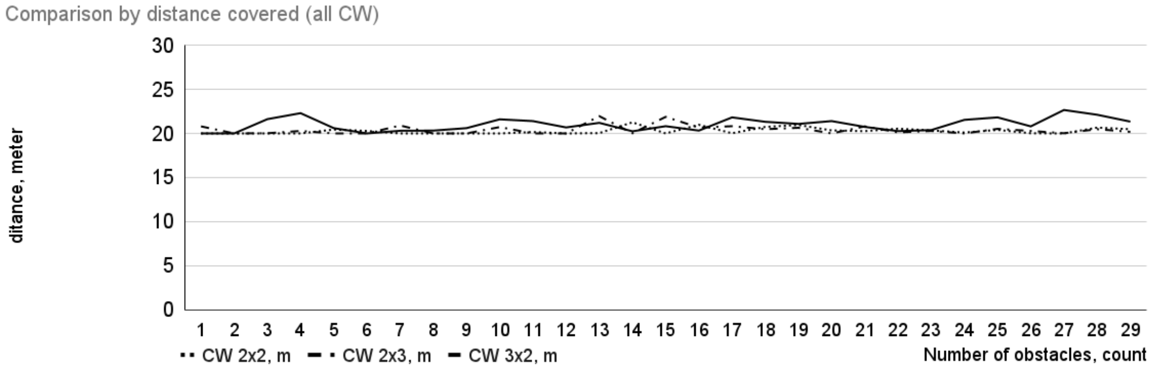

Fig. 23. Diagram of the dependence of the minimum distance travelled for the right-left algorithm on the change in the size of obstacles

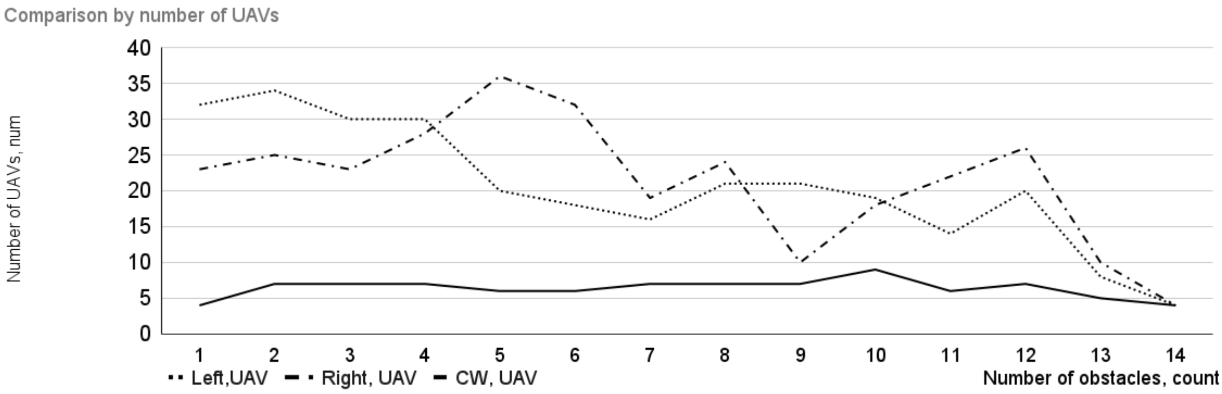

Fig. 24. Diagram of the dependence of the number of UAVs placed on the path for the guided waterfall algorithm on the change in the working area size

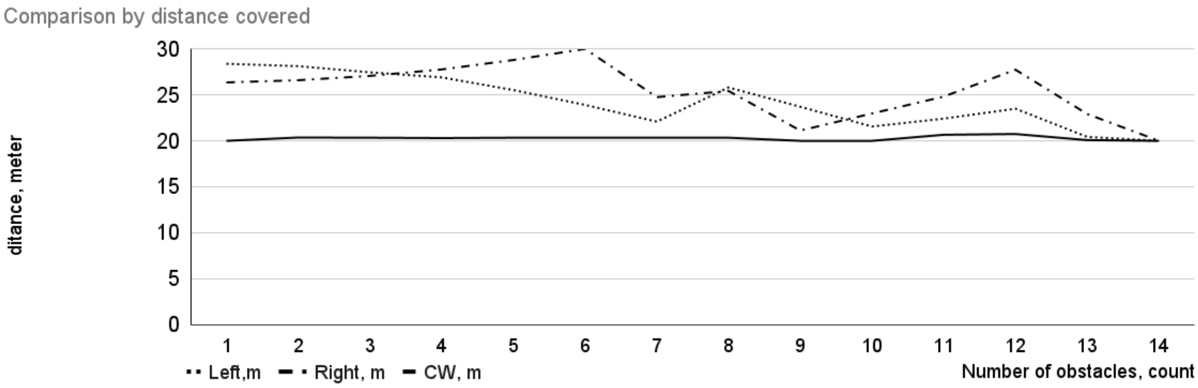

Fig. 25. Diagram of the dependence of the minimum distance travelled for the right-left algorithm on the change in the size of the working area

Analyzing the results of experiment 4, it can be noted that the guided waterfall algorithm shows a more stable performance when the working area changes. This can be explained by the fact that the recommended waterfall algorithm does not depend on the displacement of obstacles, unlike the left and right corner algorithms. However, when the working area is reduced (and the obstacles in the path are also reduced), all three algorithms show approximately the same values. This indicates that the left- and right-angle algorithms approach the efficiency of the controlled waterfall algorithm when the working area and the number of obstacles in the path are reduced. Thus, it can be noted that the controlled waterfall algorithm is more efficient than the left- and right-angle algorithms when the working area and the number of obstacles in the path increase.

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5. Discussion and recommendations

According to the experimental results, when comparing the left and right corner algorithms and the guided waterfall algorithm in terms of the minimum number of deployed UAVs and the minimum distance covered, we can conclude that:

- the guided waterfall algorithm is more efficient than rectangle-based algorithms in terms of both the minimum number of drones and the minimum distance travelled;
- algorithms based on the rectangle method may have slightly better performance with respect to the minimum distance travelled than the guided waterfall algorithm. However, the indicator of the minimum number of UAVs placed on the path is significantly increased. This can be explained by the fact that the guided waterfall algorithm is shown by the indicator of the minimum number of UAVs on the path and is based on the algorithm for finding the optimal way according to this indicator;
- the rectangle method algorithms demonstrate a significant increase in the performance of the path-finding problem when the obstacle width increases. This is because increasing the width of the obstacle significantly increases the number of blocks between points A and B; therefore, more UAVs are required to avoid obstacles and a longer distance is required. The guided waterfall algorithm also demonstrates increased performance as obstacle width increases. However, the values are insignificant and do not exceed the average effective value, unlike the rectangle-based algorithms.

Despite the advocacy of positions concerning the necessity of using UAV-based LiFi networks in the working area of critical infrastructure premises, the authors should nevertheless dwell on the problems that may arise in the development and operation of such networks, which, if possible, should be considered to a greater or lesser extent during further studies:

- LiFi relies on line-of-sight communication, meaning that the transmitter and receiver must have a clear line of sight to maintain a stable connection. In working areas with disruptions such as machinery, equipment, or other obstacles, maintaining consistent LOS can be challenging;
- the presence of other light sources, such as ambient lighting or even sunlight, can interfere with LiFi signals. Moreover, physical obstructions, such as moving machinery, can disrupt the communication link;
- UAVs are mobile devices, and working areas with obstacles may have dynamic environments with UAVs moving around, making it challenging to maintain a constant line of sight. Rapid changes in the UAVs' positions can lead to intermittent connectivity issues;
- LiFi signals can be attenuated or reflected by various surfaces. In working areas, surfaces such as metal equipment or reflective materials may cause signal degradation, affecting the reliability of communication;
- while LiFi can provide high data rates, the available bandwidth may be limited. In working areas with multiple UAVs and other connected devices, there could be competition for available bandwidth, leading to congestion and reduced performance;
- implementing LiFi technology in critical infrastructure facilities may require significant changes to existing infrastructure. Integrating LiFi with other communication technologies and ensuring seamless interoperability can be a complex task;
- LiFi transceivers on UAVs require power to operate. Ensuring that the power consumption of LiFi components is optimized to meet the operational requirements of UAVs is essential, especially considering that UAVs often have limited battery life;
- due to limited battery life, UAVs must visit battery replacement/charging stations periodically. The timely activation of the reserve UAV-based LiFi network should be provided to avoid interruptions in information transmission, which means that reserve UAVs should arrive in time for the deployment of this network. In other words, uninterrupted operation of the LiFi network can be ensured by organizing the shift duty of UAVs within this network;
- working areas can be harsh, with dust, vibrations, and temperature variations. LiFi networks must be robust enough to operate reliably under these conditions.

6. Conclusion

The main contribution of this research is a set of methods, algorithms, and software tools for providing communications between two points using LiFi technologies and a swarm of UAVs supporting these communications as transmitters in conditions of mechanical obstacles.

A solution to the communication problem for a P2P LiFi network using a UAV is presented. A series of experiments were also conducted for the controlled waterfall algorithm and the left and right corner algorithms. The experiments showed that the controlled waterfall algorithm shows better values than the left- and right-angle algorithms regarding the minimum number of drones on the path and minimum distance travelled. However, the algorithm based on the rectangle method requires less computational power. It shows approximately the same values in terms of performance as the controlled waterfall algorithm on small test sets.

The research results are not limited to the use of UAV swarms. Still, they can be extended, e.g., laying paths for ground robots and surface and underwater unmanned vehicles for developing systems for detecting and identifying explosive objects [28] or for civil applications of UAV fleets and swarms for Smart Cities [29], etc.

Future research directions are as follows:

- development of algorithms for the deployment of UAV-based LiFi networks in 2D and 3D spaces considering dynamically changed conditions, particularly variable air transparency in different parts of the area;
- development and research of model reliability and availability considering failures of UAV equipment, limitations of autonomous operation time, and the possibility of using charging stations;

investigating the possibilities for deploying UAVs with combined Wi-Fi/LiFi equipment to provide adaptive network deployment and operation algorithmsThe main contribution of this research is a set of methods, algorithms, and software tools for providing communications between two points using LiFi technologies and a swarm of UAVs supporting these communications as transmitters in conditions of mechanical obstacles.

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- investigating the possibilities for deploying UAVs with combined Wi-Fi/LiFi equipment to provide adaptive network deployment and operation algorithms.

Contributions of authors: conceptualization, methodology, formulation of tasks – **Herman Fesenko, Vyacheslav Kharchenko**; development of models and algorithms – **Kyrylo Leichenko**; verification, analysis of results, visualization, writing, original draft preparation – **Kyrylo Leichenko, Oleg Illiashenko**; review and editing – **Herman Fesenko, Vyacheslav Kharchenko**.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship, or otherwise, that could affect the research and its results presented in this paper.

Financing

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Data availability

The manuscript contains no associated data.

Use of Artificial Intelligence

The authors confirm that they did not use artificial intelligence methods while creating the presented work.

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All authors have read and agreed to the published version of this manuscript.

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РОЗГОРТАННЯ LiFi МЕРЕЖІ НА ОСНОВІ РОЮ БПЛА В УМОВАХ ПЕРЕШКОД: АЛГОРИТМИ ПОШУКУ ТРАЄКТОРІЇ ДЛЯ РОЗМІЩЕННЯ БПЛА

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Предметом дослідження є бездротові мережі на основі рою безпілотних літальних апаратів (БПЛА) в умовах перешкод. **Метою** роботи є розробка методів та програмного забезпечення для забезпечення надійного LiFi зв'язку з використанням рою БПЛА в умовах перешкод. **Завдання**: 1) сформулювати проблему забезпечення надійної LiFi мережі на основі БПЛА, вимоги до складу рою та використання БПЛА, а також припущення; 2) розробити методологію вирішення завдань дослідження; 3) розробити метод та алгоритми вирішення проблеми з урахуванням вимог, припущень та практичних обмежень; 4) дослідити алгоритми шляхом розробки програмного забезпечення для моделювання та пошуку раціонального розміщення БПЛА для забезпечення необхідних характеристик LiFi мережі на основі БПЛА; 5) навести експерименти та ілюстративні приклади застосування розробленого інструменту. Були отримані наступні **результати**. 1. Вимоги до складу та використання БПЛА для створення мереж LiFi, а також припущення та обмеження для розробки методології та вирішення завдань дослідження. 2. Метод обходу перешкод з використанням алгоритму лівого та правого кутів. 3. Метод обходу перешкод з використанням алгоритму керованого водоспаду. 4. Програмний засіб для моделювання та пошуку раціонального розміщення БПЛА для забезпечення необхідних характеристик мережі LiFi. Засіб дозволяє будувати маршрути з перешкодами у 2D просторі та порівнювати розроблені алгоритми для різних варіантів розміщення перешкод. **Висновки**. Основним внеском дослідження є комплекс методів, алгоритмів та програмних засобів для забезпечення зв'язку між двома точками з використанням LiFi технологій та роєм БПЛА, що підтримують цей зв'язок в якості передавачів в умовах механічних перешкод.

Ключові слова: безпілотний літальний апарат; рій БПЛА; LiFi мережа; середовище з перешкодами; алгоритм обходу перешкод.

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