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Design and Research of the Image Processing Unit and Telemetric Equipment for the Laser-Guided Very Short Range Air Defence Systems Field Simulator

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Abstract—**In this article, the engineering concept of the laser-guided very short range air defence system field simulator, its structure, and practical use are presented. The possibilities and advantages of the practical use of the equipment developed in tactical exercises and individual training of air defence specialists are shown. The field simulator equipment without invasion and compromising functionality into the combat air defence system has been connected and installed. The simulator performs all required shooting procedures without using combat missiles, target detection, shot execution, and maintaining the target in the sighting lens until its destruction. The field simulator reduces training process expenses and increases its efficiency. In the article, the ground control and onboard control units are presented. The units consist of target detection and its positioning, coordinate defining and data transmission (global positioning system (GPS), personal computer (PC), radio frequency (RF) transceiver), pyrotechnic charge for missile launch simulation, and target destruction devices (e.g., smoke generator), whose operating principles, functional capabilities, and work reliability are ensured on the basis of conducted research. The field simulator, which was created based on synthesising the simulator systems studied, has proven itself in practise.**

Index Terms—**Air defence personnel training equipment; Very short range air defence system field simulator; VSHORAD.**

I. INTRODUCTION

The defence of the country is the critical condition determining the possibility of a harmonious and secure development of the state and its society. One of the most essential defence systems of the state is air defence. A significant part of air defence is ground-based air defence systems (GBAD) [1]. According to the NATO classification [2], GBAD systems are divided into four levels: very short range air defence (VSHORAD), short range air defence (SHORAD), medium range air defence (MRAD), and long range air defence (LORAD).

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Especially important and famous are the VSHORAD systems. VSHORAD is an antiaircraft weapon system for defence against low-altitude targets, primarily helicopters and low-flying close-air support aircraft [3]. There are many types of VSHORAD systems. Some of them are based on infrared with sophisticated FM tracking. Others are based on a control beam when the weapon creates a laser corridor within which a missile is flying [4].

Fletcher and Chatelier [5] provided an overview of military training categories. For effective use of available air defence systems in practise, it is necessary to have a well-developed training methodology for the operation of air defence systems. Today, virtual computer simulators, firing units, and air targets (unmanned aerial vehicles (UAVs), air balloons, mortar lights, etc.) are used to train air defence systems specialists. Virtual computer simulators for initial training and support for target skills are especially useful. During the final training and air defence tactics exercises, firing units and air targets are required.

Using UAVs, balloons, mortar lights, and other air targets has many drawbacks: balloons and mortar lights are static and small targets, so radar teams cannot participate in the exercise, and only the missile launcher team is trained. Due to the small size of the target, it is often not destroyed and the assessment of the shot is subjective, based on the distance between the target and the missile. The use of combat missiles and UAVs in combat shooting exercises is costly [6].

Due to the ability of simulators to generate unfeasible situations and scenarios synthetically, they are a required tool in some areas of modern military training. Flight simulators, which are now required pilot training solutions, are the best example of such a scenario.

II. RELATED WORKS

The inside improved moving target simulator (IMTS) [7] is a training system created by Aegis Technologies Group, Inc. for the United States Army and the United States Marine Corps (USMC). The display system used in this simulator is a 40-foot-diameter hemispherical dome construction. A tiled projective surface made of multiple screen panels within the dome displays a seamless picture all around the 360-degree dome. The system can accommodate three Stinger teams of two people each and enables them to engage the target aircraft. To carry out the simulated engagements, the operators use actual Stinger launchers (dummy versions). The purpose of the system is to train operators of very short range infrared-based air defence weapons.

The inside training facility [8] for the laser-guided RBS-70 ground-based very short range missile defence system created by BAE Systems is located at the Woodside Barracks of the Australian Defence Force in South Australia. The system provides Air Defence soldiers with a completely immersive collective training environment. It continues to provide high-quality training results while saving money in logistics and ammunition. The immersive experience has improved significantly, allowing soldiers to be trained and evaluated in an air defence environment while being "distracted" by ground events. This simulator, however, does not generate the actual field polygon circumstances.

Captain Kellaway, Brendan, and Stanley [9] analyse the training tools for GBAD detachments. The Advanced Air Defence Simulator is described in depth, with a focus on functionality and characteristics. Integration of two simulators to create a collective trainer was clearly the most significant development challenge. The 3D graphics methods used to ensure that aircraft, missiles, terrain, and weather appear correlated and without delay on all display devices: the dome, internal weapon site, hand-held binoculars, target data receiver, and debrief subsystem are all carefully considered. However, this system is intended for internal instruction.

Surdu, Harrington, Black, Lynch, Schmitz, and Bracken [10] emphasised that the US Army has a major training gap for Stinger (very short range infrared guided air defence system) gunners and teams, according to the report. There is no solution that allows Stinger teams to be credited for successful engagements in large force-on-force drills if the aircraft are not outfitted with MILES detectors, which appears to be the case most of the time. The proposed system will have three major components: a custom-built FIM-92 replica with proprietary hardware and software, an Instructor Operator System (IOS) that allows trainers to grade gunners, and a set of microservices that provide high-fidelity terrain correlation, wound adjudication, and interoperability with existing training services. The analysis of the training equipment shows that there are very few high-fidelity immersive training facilities and that they are mainly created to use inside. This, in turn, provides limited training opportunities to all individuals who need that kind of training environment. For the outside usage, laser-guided simulator has not been created at all.

Dynamic analysis and synthesis methods of mechanical, electronic, laser systems and IT technologies to create tools and equipment to realise very short range air defence systems field simulator functions and operations were used. The problem of developing, researching, and using the field simulator presented in the paper is relevant in scientific and practical aspects.

According to Goetz, Vane, Solomon, and Rock [11], imaging spectroscopy, also known as hyperspectral imaging, is concerned with the measurement, analysis, and interpretation of spectra acquired from a given scene (or specific object) at a short, medium, or long distance by an airborne or satellite sensor. The concept of imaging spectroscopy originated in the 1980s, when A. F. H. Goetz and his colleagues at NASA's Jet Propulsion Laboratory began a revolution in remote sensing by developing new instruments such as the Airborne Imaging Spectrometer (AIS), then called "AVIRIS".

Synthetic aperture radar based on ground moving target detection from aircrafts, which plays an increasingly important role in battlefield surveillance, traffic surveillance, and other applications, has been analysed [12]–[14].

Liu, Cao, and Jiang [15] presented visual object tracking with partition loss schemes as a fundamental task for building automatic transport vision systems. To alleviate the drift problem caused by several intrinsic and extrinsic disturbing factors, the block-division appearance model is adaptively constructed by splitting sample region sequences into a set of subblocks. The local loss representations are extracted by discarding the low-frequency signal components in the three-dimensional discrete cosine transform domain. Moving target detection is also the basis for target tracking. In fact, it is very important to acquire the effective features of an object of a target region for advanced computer vision-based applications. Recently, the three-dimensional discrete cosine transform has shown strong properties for representing a sequence of concatenated correlated images.

Zuo, Jia, Yang, and Kasabov [16] presented detection of moving targets based on improved background subtraction of a Gaussian mixture in video images. To improve the detection accuracy of moving targets of the Gaussian mixture model (GMM) algorithm and reduce its susceptibility to noise interference under dynamic backgrounds, this paper proposes a background subtraction method based on improved GMM. The method can detect moving targets under a dynamic background in a video image, and the detection performance is better than that of the original GMM algorithm. The method consists of three stages. In the background modelling stage, the image block mean method is used to build the background model. The second stage is the detection of the moving target. To remove the influence of noise on the detection results, the denoising based on a wavelet semisoft threshold function and the mathematical morphology denoising method is used to eliminate noise interference. In the background update stage, the adaptive background update method is used to update the background. Through a simulation experiment, the improved method is subjectively and objectively better than the compared algorithms, which verifies the effectiveness and adaptability of the method.

Huang, Xia, Liao, and Yang [17] proposed an algorithm called the "keystone transform and coherently integrated cubic phase function" (KT-CICPF). The distance classifier correlation filter (DCCF)of the KT-CICPF is constructed before range cell migration correction (RCMC). In the

DCCF constructed by KT-CICPF, the energy of the moving target is dispersed into multiple range cells, resulting in defocusing of the peak of the constructed parameter estimation plane. In addition, when the RCMC is performed, the movement amount of the third-order term is ignored, resulting in parameter estimation errors.

Cesar and Farlik [18] state that the missile guidance system is one of the most important components of a missile itself and should also be reflected in a simulation environment. Therefore, tactical simulators should contain as precise missile models as possible. Unfortunately, most modern simulators use very simplified mathematical models. To bring the simulation closer to reality, the model of each missile should work according to a specific guidance method that contains real guidance equations. The article focusses on the creation and implementation of specific missile characteristics into a tactical simulation environment and outlines its usage for the future simulator of an autonomous air defence system.

In summarising, it can be assumed that the need to have field training equipment that consists of real objects (combat air defence system and real aircraft) imitating natural shooting is identified. The designed training equipment is mounted on a laser-guided air defence system and aircraft without compromising its functionalities. The field simulator simulates all functions and firing operations of the combat device - target detection and retention in sight, determination of fire position and target coordinates and their transmission using an RF transceiver, the launch of a combat missile, determination of its flight time, target destruction, etc.

III. CONCEPT OF A FIELD SIMULATOR FOR LASER-GUIDED VSHORAD SYSTEMS

The detailed field simulator concept is presented in Fig. 1. The simulator is divided into two main components: a Firing Unit (VSHORAD system) and a Target (aircraft) (in Fig. 1, 1 and 4, respectively). The field simulator equipment was connected and installed without invasion and compromising functionality into the combat air defence system and aircraft. The firing unit is a laser-guided SHORAD system.

The Ground Shooting Unit ((3), see Fig. 1) is a device consisting of a Ground Control Unit (3.4), Eyepiece Splitter (3.1), Video Camera (3.2), Image Processing Unit (3.3), RF Transceiver (3.5), and GPS Receiver (3.6). The Ground Control Unit (3.4) is a microcomputer that receives signals from the GPS Receiver (3.6), the RF Transceiver (3.5), and the Image Processing Unit (3.3).

The Video Camera ((3.2), see Fig. 1) and the Image Processing Unit (3.3) record information about the targeting process. The Ground Control Unit (3.4) (GCU) transmits information to the RF Transceiver (3.5) and Pyrotechnic Charge (2) when the target is recognised and the shoot is performed. It activates the pyrotechnic charge, and its explosion imitates a missile launch. GCU begins to simulate a missile flight to a Target (4). To imitate a missile flight path, a programme is created that calculates the movement of the target and the missile (flight time, distance, and velocity). The trajectory of a missile flight directly depends on the coordinates of the target detected by the Image Processing Unit (3.3). The GCU microcontroller reads data from the GPS Receiver (3.6) of the Ground Shooting Unit (3) and receives data from another GPS Receiver (5.4) and Altimeter (5.5) of the Onboard Target Unit (5) with the help of RF transceivers (3.5, 5.3). These data refine the simulation [19], [20].

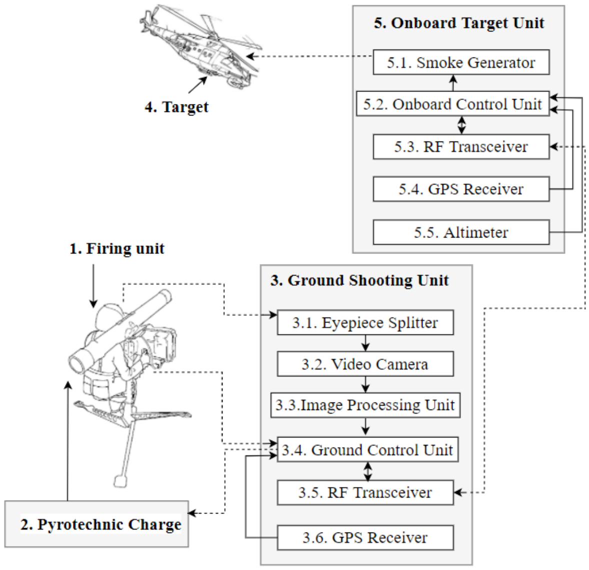


Fig. 1. Concept of the field simulator for very short range air defence systems.

These data also refine the missile flight simulation. In the simulation, when missile-target contact occurs, the Ground Control Unit ((3.4), see Fig. 1) sends a signal to the Onboard Target Unit (5), where the Onboard Control Unit (5.2) turns on the Smoke Generator, indicating that the target is destroyed. If the missile does not hit the target, the training systems receive a signal to restart the exercise [19], [21].

The training equipment maximally simulates the operation of the combat VSHORAD system, the procedures for loading, launching, and aiming missile, and also simulates the external ballistics of a real combat missile. During exercises, training equipment does not use the laser resources of the combat system [22]–[25].

IV. IMAGE PROCESSING SYSTEM

The image processing unit is used to transfer the launcher sight image to the controller. The target image is tracked with the CCD progressive video camera through the sight optical system and the eyepiece beam splitter and the video signal is transmitted from the camera to the image processing unit. The missile flight simulation trajectory depends on the coordinates of the target detected by the image processing unit. The developed image processing unit with other supporting equipment is presented in Fig. 2.

The monochrome video signal from the CCD progressive video camera enters the video front-end integrated circuit (TW9912) [26]. The image is decoded and digitised by the analog to digital converter (ADC). The image frame is written to the SRAM 1 memory. The video decoder also extracts video sync signals, which are further used for image processing unit synchronisation. The next frame of the video signal is decoded, compared with what was written before (subtraction is performed between the corresponding pixels), and the result is written to another SRAM 2 memory as a buffer. The target detection algorithm allows parallel calculations to be performed. Other algorithm operations are performed with a short delay. All calculations are performed with a single frame (40 ms) delay. When a target is detected, it is first marked in black, and the image is transmitted to the video encoder.

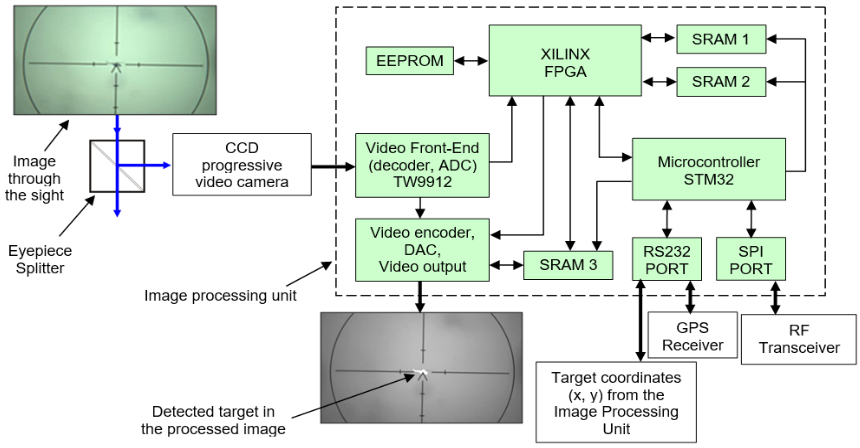


Fig. 2. Image processing unit with other supporting equipment.

The coordinates of the target are calculated by the STM32 microcontroller and transmitted to the ground control unit. The image processing unit uses a field-programmable gate array (FPGA) integrated circuit [27], [28]. It is based on a matrix of configurable logic blocks (CLBs) connected via programmable interconnections. The FPGA is reprogrammed to the desired application or functionality requirements after manufacturing. FPGA is used to implement various commonly used functions, such as integer arithmetic. It is used for fast arithmetic operations. The FPGA performs logical and arithmetic operations in the image processing unit, thus greatly speeding up calculations.

– *Experimental Research of the Image Processing Process*

To check the developed image processing unit target detection flow chart, the algorithm was created (Fig. 3). The algorithm was developed and tested with open source computer vision library (OpenCV), a software library for computer vision and machine learning. OpenCV includes many image processing functions, machine learning algorithms, and libraries for computer vision applications.

This relatively simple algorithm for finding the coordinates of a target in an image was chosen for the following reasons:

– The algorithm must be fast (calculation speed - from 25 to 30 frames per second);

– Implementation of the algorithm would require as little FPGA and microcontroller resources as possible;

– All images have one common feature: the background (sky) is blurred, and the target is bright and contrasting, mostly black.

Background subtraction is the most common algorithm for detection of moving objects [29]. Establishing the background then subtracts the current frame image from the background. If the pixel threshold is greater than or equal to a certain threshold, it is determined that the pixel area of these positions in the current image is the foreground motion area. Otherwise, it is the background area.

The algorithm starts with the frame difference method. It is a differential operation of two adjacent frames in the video sequence. To eliminate noise and smooth the image, Gaussian, median, and averaging smoothing filters were tested [30]. The averaging filter was chosen. It is very fast and does not require a lot of integrated circuit (IC) resources. The average filter moves through the image pixel-by-pixel, replacing each value with the average value of neighbouring pixels, including itself. When smoothing the image, the histogram image result is calculated. The histogram to set the threshold level is automatically used. After threshold processing, a binary image is obtained. The dilation method (morphology) fills the gap in the broken target image. The image is segmented, and the target is detected. Then, the target coordinates are found.

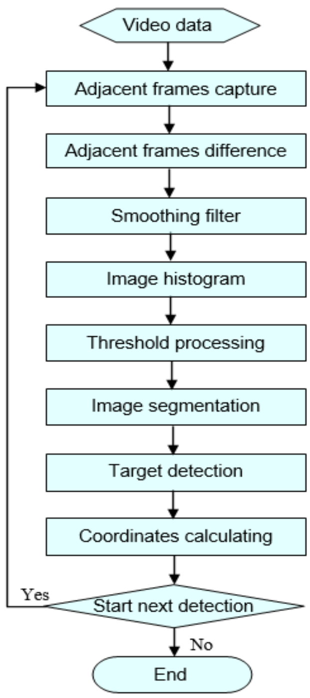
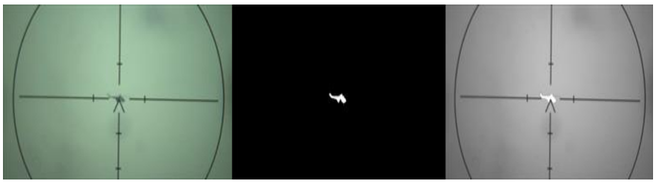


Fig. 3. Target detection flow chart.

To test the algorithm, two video films with targets of different sizes and speeds were used (Fig. 4 and Fig. 5). Each video was 5 s long (125 image frames). In all images, the programme accurately recognised the target. These tests were performed with the OpenCV programme [31].



(a) (b) (c)

Fig. 4. Target image 1 acquisition procedures: a) Initial image; b) Image with a mask after processing; c) Detected target in the initial image.

(a) (b) (c)

Fig. 5. Target image 2 acquisition procedures: a) Initial image; b) Image with a mask after processing; c) Detected target in the initial image.

V. TELEMETRIC EQUIPMENT FOR THE VSHORAD SIMULATOR

Telemetric equipment is a vital component of the developed training equipment. This system is based on the data transference between air defence systems and aircraft. Before selecting the proposer equipment, the theoretical research has been performed based on the training equipment functionality. The effective range of air defence systems depends on the type of missile used. The development of the simulator focusses on a laser-guided, very short range air defence system. During the investigation, it was determined that the laser-guided very short range air defence system missile operating distance is 200 m to 8 km. Height - from 5 m to 5 km. Therefore, the acquisition of telemetric equipment was focussed on the longest distance of 12 km [32].

A. The Algorithm for the Telemetric Parameters Estimation

The principle of operation of the VSHORAD system is based on line of sight. It is essential to evaluate in which area shootings are carried out. The shooting distance is longer if shooting in an open area or on a clear day. The distance of target decreases in a hilly area or on a cloudy day [33]. The algorithm was created for the parameter estimation of the field SHORAD simulator (Fig. 6).

Data transmission reliability and availability are the essential features of the designed VSHORAD outdoor trainers. The quality of the radio transmitter is selected and optimised to perform and shoot successfully at the target. Each state has internal procedures for radio frequency availability [34], [35].

Part of the developed firing equipment is installed on the aircraft. For this reason, the selection of the appropriate radio equipment is measured and the potential electromagnetic interference (EMI) that can degrade or even interfere with aircraft aeronautical equipment is assessed. EMI can affect cockpit radios and radar signals and interfere with pilot and control tower communication. Standards such as the RTCA DO-160 for environmental conditions, aircraft equipment test procedures, or the Department of Defence MIL-STD-461 for controlling EMI problems are designed. One of the main ways to combat EMI is to provide a variety of interchangeable units and harnesses on the line [36].

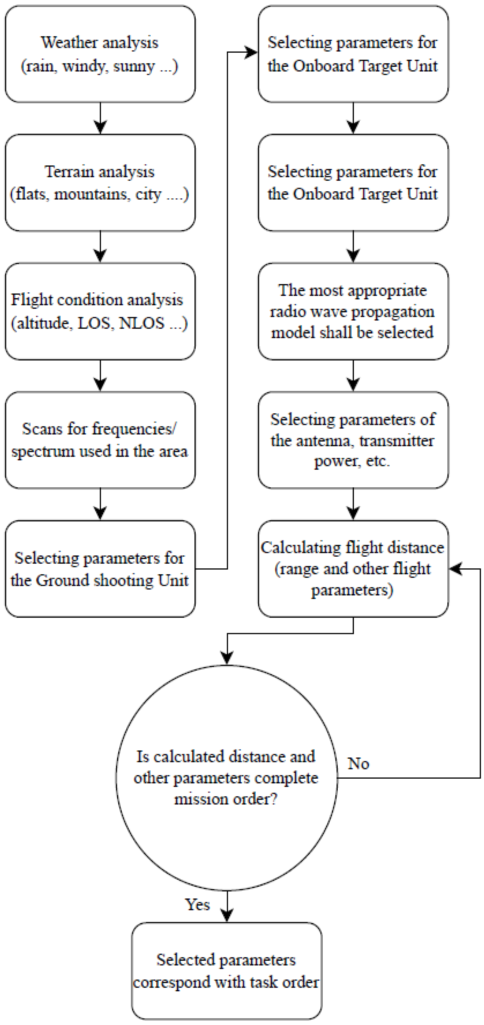


Fig. 6. Algorithm for the estimation of telemetric parameters.

B. Determination of Radio Wave Propagation Models

To select the radio wave propagation model, it is necessary to evaluate the territory of the exercises. The same model can only be used in some areas because each area has specific characteristics, such as tall buildings, etc. However, these are predominantly suited to cellular-type applications where the link is between a high base station and a low mobile station in urban, suburban, or rural environments (e.g., Hata, COST 231 Walfisch-Ikegami) or to broadcast and microwave links where both transmit and receive antennas are elevated from nearby obstructions (e.g., irregular terrain model). For each uplink, the mean RSSI level is determined. The difference between the mean and median RSSI levels is generally tiny [33], [37].

A thorough examination of the available path loss prediction and channel models for the A2A and A2S propagation channels was performed [38]. Modern models were examined and particular case studies were evaluated to understand the intrinsic character and behaviour of such channels. According to the published data, several aspects significantly impact both, including flight dynamics, distance and altitude, underlying topography, velocity and trajectories, and atmospheric impacts.

Khawaja, Guvenc, Matolak, Fiebig, and Schneckenburger [39] conducted a comprehensive survey of the propagation pathways of air to ground for UAVs. The measurement campaigns for the propagation of AG in the literature were summarised, with information on the type of channel sounding signal, its centre frequency, bandwidth, transmit power, UAV speed, UAV height and GS, link distance, elevation angle, and local GS environment characteristics provided. Statistics from the literature on air-ground channels were also presented. Various UAV propagation situations and key implementation considerations for these measures were also explored. There was a discussion of large-scale fading, local-scale fading, MIMO channel characteristics and models, and channel simulations. Finally, research directions and challenges for the future were reviewed.

According to Ahmad, Cheema, and Finlay [40], with the increasing use of UAVs in the consumer and business markets, it is proposed to help the existing terrestrial communication infrastructure for greater coverage of the wireless network. In particular, the following 5G/B5G technologies are projected to increase wireless network coverage in scenarios requiring high capacity and low latency for emergency demands, temporary coverage in hard-to-reach locations, IoT and disaster management. UAV-enabled networks are projected to play a vital role in future wireless networks, improving coverage and providing on-demand access. The study presents a complete assessment of channel modelling of UAV-enabled networks using measurement and simulation methodologies. Furthermore, possible open research topics are emphasised, and essential use cases are given that will be critical for a low functional altitude UAV enabling wireless networks, with a focus on radio propagation channel modelling.

The $D_{Apr}(\alpha)$ derived formulas for the widely used radio wave propagation models are presented below. The $D_{Apr}(\alpha)$ is the radius of coverage of the radio system in the direction α, km. The following formulas allow for finding the system coverage by evaluating signal attenuation, antenna gain, and operating frequency. The radio wave propagation models are only suitable for the locations and frequency ranges indicated in the areas. Each case is different, so other signal propagation models that may be more suitable for the selected area can be used to obtain a more accurate energy budget.

When the distance is up to 20 km, the HATA propagation model can be used in rural, suburban, and urban areas. The frequency range is 0,15 GHz to 2 GHz

$$D_{Apr}(\alpha) \leq 10^{\frac{P_S + A - P_{rib} + G_S(\alpha) - 42{,}6 - 20\log f_c}{26}}. \tag{1}$$

This Friis radio propagation model can be used in rural, suburban, and urban areas. The frequency range is 0,7 GHz to 100 GHz

$$D_{Apr}(\alpha) \leq 10^{\frac{P_S + A - P_{rib} + G_S(\alpha) + G_t(\alpha) - 92{,}45 - 20\log(f)}{20}}. \tag{2}$$

The SUI radio propagation model can be used in rural (γ = 1,8), suburban (γ = 3,3), and urban (γ = 4,7) areas. The frequency range is 1 GHz to 6 GHz

$$D_{Apr}(\alpha) \leq \left(10^{\frac{P_S + A - P_{rib} + G_S(\alpha) + G_t(\alpha) - x_f - x_h - L_{fso} - S}{10\gamma}} \right) \times d_0. \tag{3}$$

This COST-HATA model can be used in suburban, urban areas. The frequency range is 2 GHz

$$D_{Apr}(\alpha) \leq 10^{\frac{P_{rib} - P_S - A - G_S(\alpha) - G_t(\alpha) + 46{,}3 - 33{,}9\log f_c + 13{,}83\log h_{tx} + a - c}{44{,}9 - 6{,}55\log h_{tx}}} \tag{4}$$

when

$$a = (1{,}1\log f_c - 0{,}7)h_{rx} - 1{,}56\log f_c - 0{,}8. \tag{5}$$

C. Estimation of the Telemetric Equipment Signal Level

To select the appropriate radio equipment, the calculation of the signal level study of the telemetric equipment was performed. The wireless communication system was theoretically modelled using EDX Signal ProTM software. The field investigation between the ground control unit and the onboard control unit was performed to check the theoretical studies. During the experimental investigation, the area was randomly selected. This research is important to determine the antenna's required gain and height to accomplish the task in a certain area. The calculation model for the parameter estimation of the communication system between the target and the air defence system is shown in Fig. 7.

After receiving the report from the Headquarters, an analysis of the task and the area of the operation is carried out.

– What is the size of the operation area? What is the relief of the territory? Is this area densely populated? Are there tall buildings, high mountains?
– Analysis of the friendly area is carried out - the most suitable place is searched for where the ground control unit can be built. Is there a reliable connection between the target and the air defence system?
– An analysis of neutral territory is carried out, looking for the highest places in this territory. It can also be analysed with a spectrum analyser to determine whether the 2.4 GHz frequency band is not polluted in the area.

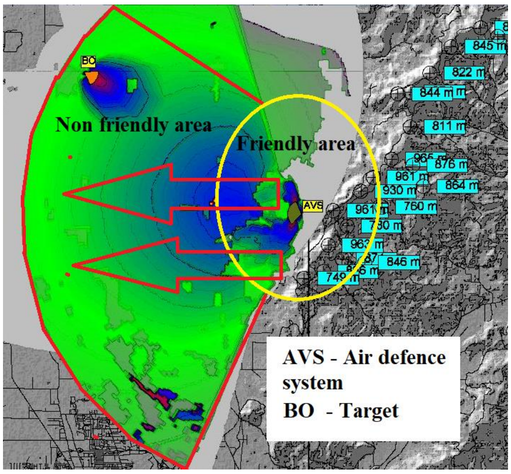


Fig. 7. Communication system between the target and air defence system.

D. Theoretical Research

The most common frequency in wireless communication systems today is 2.4 GHz. The wireless signal transmission system was modelled using EDX Signal ProTM software. The study is carried out by analysing the dependence of the signal level on the distance. It is necessary to calculate the power budget and antenna incompatibility losses, which, after calculation, leave a reserve of signal power.

During the research, the LMDS 90 hb base station antenna with a wide radiation pattern was selected. The directivity of this antenna is 90 °. Vertical signal polarisation was used.

In the simulation, the antenna height of the ground control unit is chosen to be three meters. In practise, this is achieved by using a special tripod antenna holder. We assume that the remotely controlled aircraft has taken off at an altitude of 250 m. By changing the power of the transmitter, we calculate the distance, the level of signal in the receiver, and the availability of the connection. Connection deliverability starts to be evaluated after reaching a value of at least 99.99 %. The investigation results are presented in Table I.

TABLE I. INVESTIGATION RESULTS.

Test No.	AVS antenna gain, dBi	Distance between UAV and AVS, km	RSL, dBmW	Communication availability, %
1	3	0,4	-96,74	99,9999
2	6	1	-96,78	99,9999
3	9	4	96,64	99,9999
4	12	8	-96,22	99,9982
5	15	14	-94,11	99,9977
6	21	17	-93,48	99,9971
7	24	20	-93,01	99,996
8	27	23	-92,5	99,9949
9	30	26	-91,67	99,9945
10	31	27	-91,41	99,9943
11	32	28	-91,33	99,9935
12	33	29	-91,1	99,9932

Changing the power of the transmitter simulates the maximum flight distance. With an omnidirectional antenna, to achieve the same distance, it would be necessary to use an even higher gain antenna because increasing the gain of the antenna increases the level of noise received in different directions. Furthermore, omnidirectional antennas have limited gain (up to 18 dBi), so it is not possible to achieve the maximum distance. The maximum distance simulated by increasing the height of the ground control unit antenna and its gain to 33 dBi was about 29 km. The summarised simulation results are presented.

Figure 8 presents the dependence of communication availability on the distance between the air defence system and the target. When distance increases, communication availability gradually decreases due to loss of radio signals, which increases at long distances.

Figure 9 presents the dependence of the radio signal level on the distance between the air defence system and the target. The signal level was determined to gradually decrease, increasing the distance.

Figure 10 presents the dependence of the distance between the air defence system and the target on the gain of the antenna gain of the air defence system. Increasing the gain of the antenna of the air defence system by 6 dBi doubles the distance.

As the distance increases, communication availability gradually decreases due to loss of radio signals, which increase over long distances. Calculations with specialised EDX Signal ProTM software show that increasing the gain by 3 dBi increases the distance by an average of 1.5 times. The radio signal level decreases by about 3 dB with increasing distance, while the communication performance decreases by 0.0033 %.

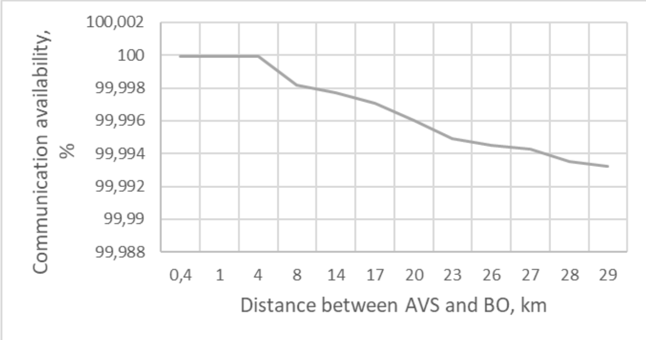


Fig. 8. Communication availability on the distance between the air defence system and the target.

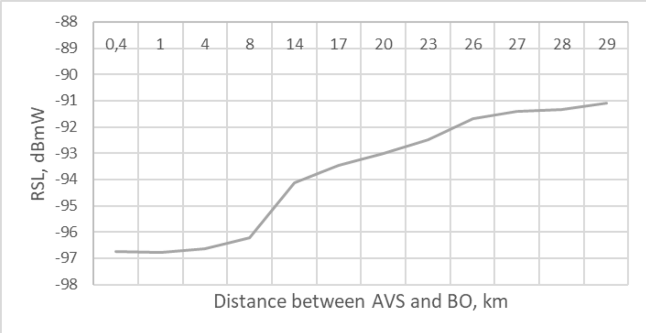


Fig. 9. Dependence of the radio signal level on the distance between the air defence system and the target.

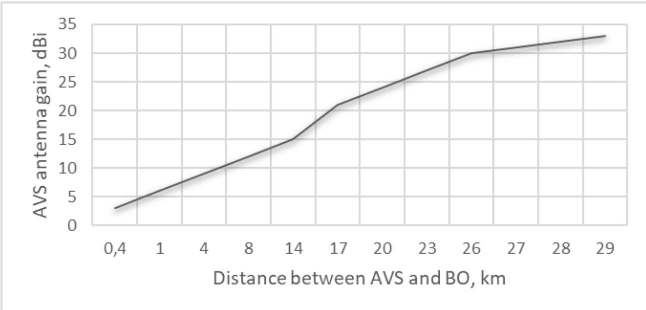


Fig. 10. Dependence of the distance between the air defence system and the target on the gain of the air defence system antenna gain.

E. Field Testing

To evaluate as accurately as possible the wireless communication between the remotely controlled aircraft and the ground control unit and the dependencies on the parameters of the target system, which can be modified before starting the missions, experimental tests were carried out in field conditions. The experiment was carried out in two types of areas, flatland and forest. During the research, we measured the distance between the target and the air defence system:

1. In the flatland area, when the system: a. according to the developed algorithm uses a 9 dBi antenna; b. according to the developed algorithm and using a 12 dBi antenna;
2. In a forested area, when the system: a. according to the developed algorithm and using a 9 dBi antenna; b. according to the developed algorithm and using a 12 dBi antenna.

Relatively inexpensive and freely available hardware was used for the experiments: UAV - SYMA X56W: operational frequency - 2,4 GHz, weight - 732 g, size - 21,5 cm × 21,5 cm × 5,5 cm, antenna gain - 2 dBi. Additional antenna 9 dBi: frequency - 2,4 GHz–2,5 GHz, directionality - omnidirectional, gain - 9 dBi, height - 38 cm. Additional antenna 12 dBi: frequency - 2,4 GHz–5 GHz, directionality - sectoral, gain - 12 dBi, height - 2 m. AVS antenna height - 2,6 m, UAV height - 25 m, transmitter power - 13 dbm.

The study was carried out in two types of areas, flatlands and woodlands. The territory of the flatland was chosen in the countryside, in the Kaunas district. Location coordinates 54.967176, 23.84259. The research was carried out on a sunny evening at a temperature of 17 °C and a wind of 2 m/s. The wooded area was chosen in the Kleboniskis forest in Kaunas district. Location coordinates 54.94358, 23.92365. The research was carried out on a sunny evening at a temperature of 16 °C and a wind of 2 m/s.

The research in flatland conditions is presented in Fig. 11 and the research in forest conditions in Fig. 12.

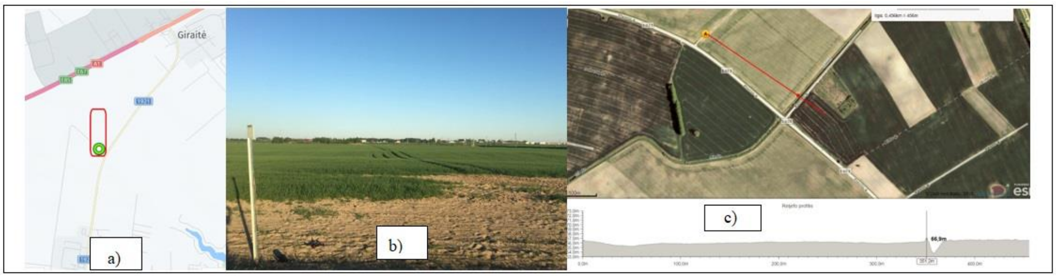


Fig. 11. The research in flatland conditions: (a) A representation of the area on the map; (b) A photo of the area showing the installed sectoral antenna directed to the research field; (c) A representation of the relief of the area with a section of the route.

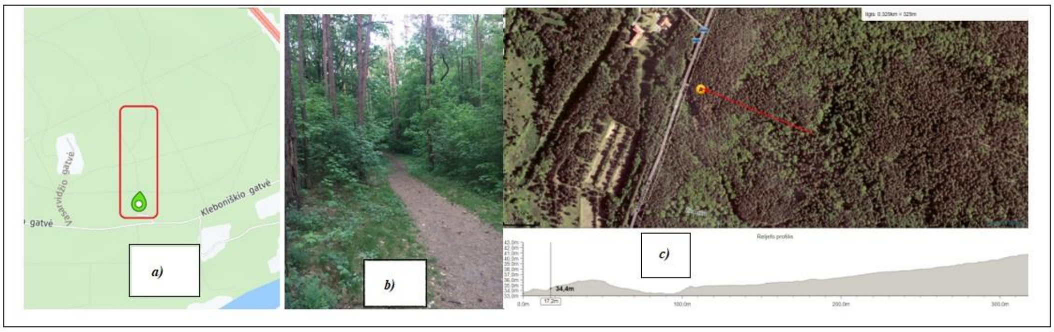


Fig. 12. The research in forest conditions: (a) A representation of the area on the map; (b) A photo of the area with a view of the forest; (c) A representation of the relief of the area with a section of the route.

VI. Results

During the research, it was determined that the flight distance directly depends on the antenna gain, the type of terrain, the directivity of the antenna, and the use of the live video broadcasting function. The comparison of theoretical and experimental research results is presented in Fig. 13 and Table II.

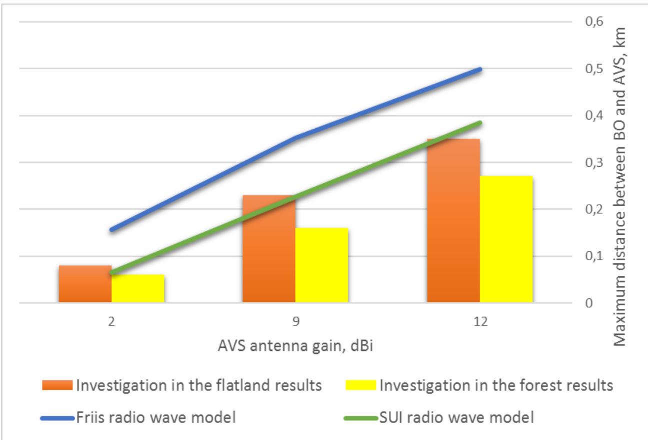


Fig. 13. Investigation results.

After improving the ground control unit and installing an omnidirectional antenna, the 9 dBi distance increased 2.9 times, and after installing a 12 dBi antenna, the distance increased 4.4 times compared to the initial parameters of the ground control unit.

TABLE II. INVESTIGATION RESULTS.

Test No.	AVS antenna gain, dBi	Distance between UAV and AVS, km	PSL, dBm	Distance differences, times	Terrain type
1	2	0,08	-93	1,00	Flatland
2	9	0,23		2,88	Flatland
3	12	0,35		4,38	Flatland
4	2	0,06		1,00	Forest
5	9	0,16		2,67	Forest
6	12	0,27		4,50	Forest
7	2	0,16		2,00	Friis
8	9	0,35		4,38	Friis
9	12	0,50		6,25	Friis
10	2	0,07		0,88	SUI
11	9	0,23		2,88	SUI
12	12	0,38		4,75	SUI

From Fig. 13, we can see that the aircraft with the same parameters flies further in the flatland since there are no obstacles between the target and the air defence system. When performing the task analysis, it is necessary to assess where the flight will be performed accurately. Otherwise, the probability of losing the aircraft increases.

After the study in field conditions and comparing the results obtained with the SUI and Friis radio wave propagation models, it was found that with 9 dBi amplification of the ground control unit antenna, the SUI model predicts the same distance as was obtained during the study in field conditions in the territory of the plains. The Friis model at 9 dBi antenna gain predicts a two-times greater maximum flight distance compared to the results obtained during the study in the plains area under field conditions.

The results of the experimental study were compared with the theoretical results. The air defence system antenna gain of 9 dBi, with the SUI model, predicts the same distance as was obtained during the field survey in the flatland area. The Friis model at 9 dBi antenna gain predicts a two-times greater maximum flight distance than the results obtained during the study in a flatland area.

The constructed distance increase algorithm was tested during the research in field conditions. The surrounding buildings, trees, and terrain strongly influence the wireless connection (as indicated in the algorithm). Shooting with the VSHORAD system was carried out under line of sight conditions. The possible telemetric equipment for the developed training equipment was determined.

VII. DISCUSSION

To make the best use of available air defence systems in practise, it is necessary to have a well-developed methodology for training specialists on how to operate air defence systems [5]. Due to unknown reasons, there is no field training equipment in the market for the laser-guided, very short range air defence system. However, similar solutions have been described and compared against ours in the other articles, but no one focused on laser-guided air defence systems. Creating this simulator as accurately as possible requires deep syntese analysis of different areas such as electronics, mechanics, mechatronics, etc.

VIII. CONCLUSIONS

1. Analysis has shown that the image processing unit for the very short range air defence system field simulator is very complex. A prototype of a real-time video image processing algorithm was developed. The programme accurately recognised the target.
2. The data transmission system (GPS, PC, RF transceiver) was created. Research on this system showed that a high-quality directional antenna and a powerful transmitter are needed to achieve the maximum distance between the target and the air defence unit. An antenna tracking and alignment system is necessary for longer distances (>2 km). An omnidirectional antenna requires an equivalent or higher gain to achieve the same distance as a directional antenna. However, the noise level received in different directions increases when the antenna gains increase. In addition, omnidirectional antennas have limited gain (up to 18 dBi), so achieving the maximum distance with them is impossible.
3. Calculations with specialised EDX Signal ProTM software show that increasing the gain by 3 dBi increases the distance by an average of 1.5 times as the distance between the air defence system and the target increases. The level of the radio signal decreases by about 3 dB with increasing distance. Communication performance decreases by 0.0033 %.
4. Training equipment was presented intended to train in the field (polygons), which simulates natural shooting conditions. The equipment presented in this research is new and will successfully complement traditional missile training equipment. The equipment is cheap and would effectively improve the training process of air defence personnel, thus strengthening the defence capability of the country.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

[1] "Joint Publication 2-01.1: Joint Tactics, Techniques, and Procedures for Intelligence Support to Targeting", Joint Chiefs of Staff, 2003.

[2] "Allied Joint Doctrine for Air and Space Operations (AJP-3.3)", NATO Standard, Edition B Version 1, pp. 1–100, 2016.

[3] "Joint warfare publication 3-63", Joint Warfare Publication 3-63 (JWP 3-63) Jul. 2003 ed. is promulgated, The Joint Doctrine & Concepts Centre MoD.

[4] P. J. Hutchings and N. J. Street, "Future Short Range Ground-Based Air Defence: System Drivers, Characteristics and Architectures", Defense Technical Information Center Compilation Part Notice Airspace Management Systems Department, Defence Evaluation and Research Agency, St. Andrew's Road, Malvern, WR14 3PS, UK, 2000.

[5] J. D. Fletcher and P. R. Chatelier, "An overview of military training", IDA Document D-2514, Institute for Defense Analyses, 2000. DOI: 10.21236/ADA408439.

[6] *Air Defense Artillery Reference Handbook*, Field Manual No. 3-01.11 (FM 44-100-2), Headquarters, Department of the Army Washington, DC, 31 Oct. 2000.

[7] AD0575 Edition 6 Final Examination, Lesson 3: Stinger Training and Training Devices. [Online]. Available: https://www.globalsecurity.org/military/library/policy/army/accp/ad0575/lesson3.htm

[8] Advanced Air Defense Simulator, BAE Systems, Bohemia Interactive Simulations. [Online]. Available: https://bisimulations.com/company/customer-showcase/advanced-air-defense-simulator

[9] Capts. Kellaway, Brendan and Mr. Dax Lukas Stanley, "The Advanced Air Defence Simulator for the Australian Army", 2005.

[10] J. R. Surdu, D. Harrington, J. Black, T. Lynch, W. Schmitz, and J. Bracken, "Low altitude air defense training system", in *Proc. of 2020 Winter Simulation Conference (WSC)*, 2020, pp. 1974–1982. DOI: 10.1109/WSC48552.2020.9384020.

[11] A. F. H. Goetz, G. Vane, J. E. Solomon, and B. N. Rock, "Imaging spectrometry for earth remote sensing", *Science*, vol. 228, no. 4704, pp. 1147−1153, 1985. DOI: 10.1126/science.228.4704.1147.

[12] A. Budillon, C. H. Gierull, V. Pascazio, and G. Schirinzi, "Along-track interferometric SAR systems for ground-moving target indication: Achievements, potentials, and outlook", *IEEE Geosci. Remote Sens. Mag.*, vol. 8, pp. 46–63, 2020. DOI: 10.1109/MGRS.2019.2957600.

[13] P. Huang, X. Zhang, Z. Zou, X. Liu, G. Liao, and H. Fan, "Road-aided along-track baseline estimation in a multichannel SAR-GMTI system", *IEEE Geosci. Remote Sens. Lett.*, vol. 18, no. 8, pp. 1416–1420, 2021. DOI: 10.1109/LGRS.2020.3003443.

[14] C. H. Gierull, "Closed-form expressions for InSAR sample statistics and its application to non-Gaussian data", *IEEE Trans. Geosci. Remote Sens.*, vol. 59, no. 5, pp. 3967–3980, 2021. DOI: 10.1109/TGRS.2020.3014853.

[15] T. Liu, X. Cao, and J. Jiang, "Visual object tracking with partition loss schemes", *IEEE Trans. Intell. Transp. Syst.*, vol. 18, no. 3, pp. 633–642, 2017. DOI: 10.1109/TITS.2016.2585663.

[16] J. Zuo, Z. Jia, J. Yang, and N. Kasabov, "Moving target detection based on improved Gaussian mixture background subtraction in video images", *IEEE Access*, vol. 7, pp. 152612–152623, 2019. DOI: 10.1109/ACCESS.2019.2946230.

[17] P. Huang, X.-G. Xia, G. Liao, and Z. Yang, "Ground moving target imaging based on keystone transform and coherently integrated CPF with a single-channel SAR", *IEEE Journal of Selected Topics in*

Applied Earth Observations and Remote Sensing, vol. 10, no. 12, pp. 5686–5694, 2017. DOI: 10.1109/JSTARS.2017.2742580.

[18] J. Casar and J. Farlik, “The possibilities and usage of missile path mathematical modelling for the utilization in future autonomous air defense systems simulators”, in *Proc. of Modelling and Simulation for Autonomous Systems: 6th International Conference, MESAS 2019*, 2019, pp. 253–261. DOI: 10.1007/978-3-030-43890-6_20.

[19] F.-j. Meng, Y.-q. Li, F.-m. Shao, G.-h. Yuan, and J.-y. Dai, “Visual-simulation region proposal and generative adversarial network based ground military target recognition”, *Defence Technology*, vol. 18, no. 11, pp. 2083–2096, 2022. DOI: 10.1016/j.dt.2021.07.001.

[20] C. Cheng, X.-d. Zhou, M. Gao, Z.-l. Zong, Y.-x. Ji, and B. Yu, “Research on monopulse forward-looking high-resolution imaging algorithm based on adaptive iteration”, *Defence Technology*, vol. 16, no. 1, pp. 158–171, 2020. DOI: 10.1016/j.dt.2019.06.008.

[21] M. Salfer and C. Eckert, “Attack surface and vulnerability assessment of automotive Electronic Control Units”, in *Proc. of 2015 12th International Joint Conference on e-Business and Telecommunications (ICETE)*, 2015, pp. 317–326. DOI: 10.5220/0005550003170326.

[22] X.-d. Guo *et al.*, “Research on DSO vision positioning technology based on binocular stereo panoramic vision system”, *Defence Technology*, vol. 18, no. 4, pp. 593–603, 2022. DOI: 10.1016/j.dt.2021.12.010.

[23] H.-f. Dai, H.-w. Bian, R.-y. Wang, and H. Ma, “An INS/GNSS integrated navigation in GNSS denied environment using recurrent neural network”, *Defence Technology*, vol. 16, no. 2, pp. 334–340, 2020. DOI: 10.1016/j.dt.2019.08.011.

[24] A. Fedaravičius, K. Jasas, E. Sližys, and A. Survila, “Modeling of the missile launch dynamic processes in short-range air defense system”, *Mechanika*, vol. 28, no. 1, pp. 32–37, 2022. DOI: 10.5755/j02.mech.29266.

[25] Portable anti-aircraft missile system RBS-70, Missilery info. [Online]. Available: https://en.missilery.info/missile/rbs70

[26] T. S. Waykole and Y. K. Jain, “Detecting and tracking of moving objects from video”, *Int. J. Comput. Appl.*, vol. 81, no. 18, pp. 23–28, 2014. DOI: 10.5120/14224-2410.

[27] D. G. Bailey, *Image Processing Using FPGAs*. MDPI AG, 2019. DOI: 10.3390/jimaging5050053.

[28] M. Baker, K. Goldblatt, and S. Knapp, *Spartan-3 Platform FPGA Handbook*. XILINX, 2003.

[29] Z. Lu, D. Kong, and X. Li, “A method for moving object detection based on background subtraction and three-frame differencing”, *Computer Measurement and Control*, vol. 21, no. 12, pp. 3315–3318, 2013.

[30] C. Solomon and T. Breckon, *Fundamentals of Digital Image Processing: A Practical Approach with Examples in Matlab*. John Wiley & Sons, Ltd, 2010. DOI: 10.1002/9780470689776.

[31] D. M. Escriva, P. Joshi, and V. G. Mendonca, and R. Shilkrot, *Building Computer Vision Projects with OpenCV 4 and C++: Implement Complex Computer Vision Algorithms and Explore Deep Learning and Face Detection*. Packt Publishing, 2019.

[32] C. Foss, *Janes Land-Based Air Defence 1992-93*. Jane’s Information Group, 1992.

[33] F. J. Oluwole and O. Y. Olajide, “Radio frequency propagation mechanisms and empirical models for hilly areas”, *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 3, no. 3, pp. 372–376, 2013. DOI: 10.11591/ijece.v3i3.2519.

[34] D. Niyato, Q. Dong, P. Wang, and E. Hossain, “Optimizations of power consumption and supply in the smart grid: Analysis of the impact of data communication reliability”, *IEEE Transactions on Smart Grid*, vol. 4, no. 1, pp. 21–35, 2013. DOI: 10.1109/TSG.2012.2224677.

[35] F. Cadini, G. L. Agliardi, and E. Zio, “A modeling and simulation framework for the reliability/availability assessment of a power transmission grid subject to cascading failures under extreme weather conditions”, *Applied Energy*, vol. 185, part 1, pp. 267–279, 2017. DOI: 10.1016/j.apenergy.2016.10.086.

[36] M. L. Shooman, “A study of occurrence rates of EMI to aircraft with a focus on HIRF”, in *[1993 Proceedings] AIAA/IEEE Digital Avionics Systems Conference*, 1993, pp. 191–196. DOI: 10.1109/DASC.1993.283548.

[37] N. Shabbir, M. T. Sadiq, H. Kashif, and R. Ullah, “Comparison of radio propagation models for long term evolution (LTE) network”, 2011. DOI: 10.48550/arXiv.1110.1519.

[38] N. Moraitis, K. Psychogios, and A. D. Panagopoulos, “A survey of path loss prediction and channel models for unmanned aerial systems for system-level simulations”, *Sensors*, vol. 23, no. 10, p. 4775, 2023. DOI: 10.3390/s23104775.

[39] W. Khawaja, I. Guvenc, D. W. Matolak, U.-C. Fiebig, and N. Schneckenburger, “A survey of air-to-ground propagation channel modeling for unmanned aerial vehicles”, *IEEE Communications Surveys & Tutorials*, vol. 21, no. 3, pp. 2361–2391, thirdquarter 2019. DOI: 10.1109/COMST.2019.2915069.

[40] A. Ahmad, A. A. Cheema, and D. Finlay, “A survey of radio propagation channel modelling for low altitude flying base stations”, *Comput. Networks*, vol. 171, art. 107122, 2020. DOI: 10.1016/j.comnet.2020.107122.