drones

Article

Hostile UAV Detection and Neutralization Using a UAV System

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Abstract: The technologies of Unmanned Aerial Vehicles (UAVs) have seen extremely rapid development in recent years. UAV technologies are being developed much faster than the means of their legislation. There have been many means of UAV detection and neutralization proposed in recent research; nonetheless, all of them have serious disadvantages. The essential problems in the detection of UAVs is the small size of UAVs, weak radio wave reflection, weak radio signal, and sound emitting. The main problem of conventional UAV countermeasures is the short detection and neutralization range. The authors propose the concept of the airborne counter-UAV platform (consisting of several vehicles) with radar. We use a low-cost marine radar with a high resolution 2 m wide antenna, embedded into the wing. Radar scanning is implemented by changing the heading of the aircraft. For the countermeasures, the authors suggest using a small rotorcraft UAV carried by a bigger fixed-wing one. A mathematical model that allows the calculation of the coordinates of the detected drone while scanning the environment in a moving UAV with radar was created. Furthermore, the results of integrated radar performance with a detected drone and the results of successful neutralization experiments of different UAVs were achieved.

Keywords: unmanned aerial vehicles; marine solid-state radar; UAV detection; drone countermeasures

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1. Introduction

The technologies of Unmanned Aerial Vehicles (UAVs) have seen extremely rapid development in recent years. The field of implementation of UAVs is especially wide, from "consumer drones" to intricate scientific or military applications [1]. Unfortunately, as with any other technology, the development of UAVs provides not only benefits but also threats to privacy and public safety. UAVs pose a massive security risk to airports and other critical infrastructure [2,3]. They can also be used to smuggle illicit goods, such as drugs [4], or even be utilized as weapons by terrorists. As experience in the Ukraine conflict shows, UAVs are actively implemented by both sides in military operations, and neutralization of UAVs is especially relevant [5,6].

UAV technologies are being developed much faster than is the means of their legislation. For example, the electronic UAV control system U-SPACE is only in the concept stage at the moment [7]. To overcome UAV-related challenges, relying only on control and management measures is not enough; effective means of detection and neutralization are necessary. There are many means of UAV detection and neutralization There are four main technologies of detection: optical in various bands [8,9]; passive acoustic [10]; passive radio-receiving emitted radio radiation from the UAV [11]; and active radio-using radars [12]. The possibilities for neutralizing the detected drones are examined in [6,13,14]. Nonetheless, all of them have some disadvantages.

The essential problems in the detection of UAVs are the small size of UAVs, weak radio signal and sound emission, and weak radio wave reflection due to the composite materials used. Utilizing a radar for UAV detection is preferable as it is robust to environmental conditions such as darkness, fog, rain, and noise, compared to alternative solutions. Many solutions are proposed where different types of radars operating in different frequency ranges can be applied to drone detection [15–17].

Usually, the means for UAV neutralization are located on the ground and have a very limited range. There are efforts to implement other UAVs for neutralization, but there is always a problem in (hunted) UAV detection; pointing and control in a fast-changing environment in the air. Therefore, at the moment, there are no fully effective solutions to detecting and neutralizing UAVs.

A radar integrated into the UAV can be used to solve this problem. The application of UAVs with various kinds of sensors is a highly investigated field. It is mostly used to monitor the environment using radar images [18–20]. These radars use SAR technology. Due to the SAR radar requiring resource-intensive calculations (usually not in real-time) being side or down-looking, this technology is not suited for the airborne detection of drones. The radar in [21] is designed to detect and avoid obstacles by using MIMO (multiple input, multiple outputs) technology at 76 GHz. In [15], the authors achieved detection up to a 150 m range of small UAVs from the ground using mm-wave MIMO radar. Due to the relatively small size, similar systems can be potentially be used in UAVs at short ranges, where a higher accuracy of distance measurement is required.

Often, drone radars are specifically designed for UAVs, which are small enough and use little energy, as they receive it from batteries [22]. In some cases, only passive radars are used, which receive signals using FM broadcasting [23], VHF [24] or UHF [25] frequency bands. In order to use low-frequency bands (mostly FM bands) for passive radars, software-defined radio equipment or custom digital receivers combining a front-end digitizer and FPGA-based real-time data signal processing software are usually used.

Our proposed idea is to integrate a radar into a UAV and turn the unmanned aircraft into a radar itself. A similar concept is more widely studied in [23]. However, our proposed case will scan the area in a 360-degree rotation like a conventional ground-based radar, thus leaving no blind spots. An additional solution can be integrated (into the same radar drone or a different vehicle) to allow tracking and disrupting the mission of detected drones, and in the best case, physically neutralize the unwanted drone. There are not many studies of systems that use drones to track and eliminate other drones and, as an example, the control concept for the drone swarm is presented [5], in which a swarm of drones surrounds the intruder and can limit the intruder's operational capabilities more safely, but this is only implemented at the level of conceptual and control algorithms.

The relevance and novelty of the work are related to the possibility of not adding a radar to the drone, but to turn the aircraft itself into a radar that can perform the task of scanning an area in a certain place and quickly leave the scanning area. To achieve this goal, an innovative 3D scanning system was developed, which is based on a co-authored patent, application No.: WO201900003194A1 [26].

The paper is structured in the following manner: a mathematical model of the detected UAV coordinates estimation, UAV embedded radar solution, experimental setup, results with discussion and conclusions. In the paper, the authors reveal the characteristics of implementing the countermeasure system and the results obtained.

2. Proposed Solution

In this paper, the authors want to present a solution that allows integrating the radar into a fixed-wing UAV structure, thus not adding radar externally to the plane, but building the radar into the plane structure and performing the rotation of the radar by manoeuvring the plane itself. At the same time, the authors foresee integrating an additional drone in the plane, which will allow neutralisation of the detected UAVs. Here, the authors propose a UAV countermeasure platform.

The main problems in the realization of this concept are the difficulties in the tracking of target UAVs by optical or short-distance radar scanning means. Implementation of an onboard radar could simplify this task considerably. A radar mounted on a UAV would also allow much broader use cases in environmental monitoring, reconnaissance or search and rescue missions. Radars currently implemented on UAVs are heavy, bulky, expensive [27] or not effective for large distances (X band radars). Therefore, the authors suggest embedding the radar into fixed-wing UAVs capable of detecting small UAVs (drones etc.) and carrying the "hunter" drone UAV. To maximize the endurance of the vehicle we suggest mounting the equipment on a fixed-wing (aeroplane) type unmanned aircraft with a piston power plant, which allows reaching a maximal endurance of up to 24 h in some cases.

To decrease the price of the "hunter" drone UAV system we suggest the implementation of mass-produced consumer-level ship (marine) radars, with additional modifications for their implementation on UAVs. The ability to detect UAVs by marine radars is presented in [17]. The authors used an FMCW marine radar, which was successfully used together with UAVs; however, the authors encountered that the radar was prone to noise which was difficult to eliminate. Such radars, depending on their parameters, are evaluated to cost from three to fifteen thousand euros and have a mass of 7 to 25 kg. Such mass might be too big for small-size UAVs. In addition, the bulky radar antenna creates significant drag in high-speed flight. To solve these problems, a concept is suggested that allows complete removal of the radar antenna mechanical tracking (rotation) mechanism by integrating the radar antenna into the leading edge of the fixed wing of an unmanned aircraft. The aerial scanning by radar (rotation of the antenna) will be performed by choosing the special trajectory of aircraft flight as presented in Figure 1.

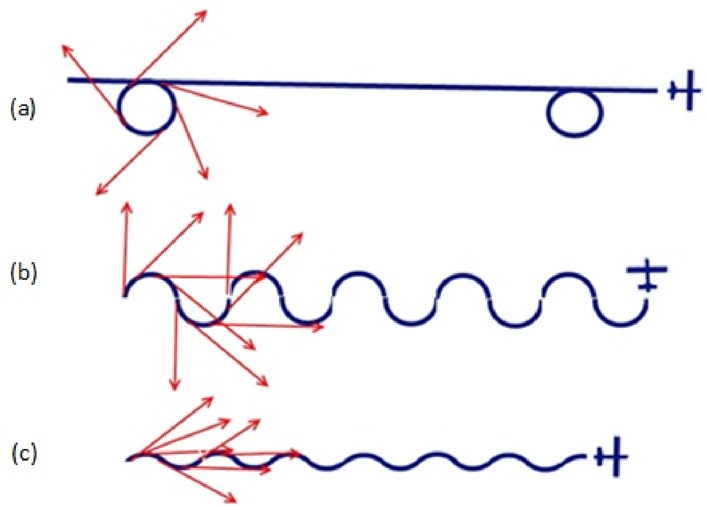

Figure 1. Possible manoeuvring routes of a fixed-wing UAV with an embedded radar, where (**a**). periodical UAV scanning-circling in-route, (**b**). half circle rotation with 180° scanning in-route, and (**c**). 90° scanning in flight direction with quick turns of UAV.

The methodology for the determination of all three coordinates of the target using a simple 2D radar with a special flat curved flight pattern has been presented in the co-authors' patent application [26]. This concept is based on scanning using two inclined radar beams; narrow in the horizontal plane and wide in the vertical plane (fan beams).

If we have two tilted fan beams (S′ and S″ in Figure 2a) on the roll axis, directions to the target may be different on each beam (if the target and radar are in different altitudes). It is possible to find the target's altitude H if the distance to the target R and the angle of the target's responses (5, 5′ of radar plot 4 in Figure 2c) between two beams γ are known, as expressed in (1). This idea can be implemented by using X-shaped or two V-shaped electrically scanned antennas 1′ and 1″ in the UAV (2″) as shown in Figure 2c.

$$H = \frac{R \tan \phi_1 \tan \phi_2 \sin \gamma}{\sqrt{\tan^2 \phi_1 + \tan^2 \phi_2 + 2 \tan \phi_1 \tan \phi_2 \cos \gamma + (\tan \phi_1 \tan \phi_2 \sin \gamma)^2}}. \tag{1}$$

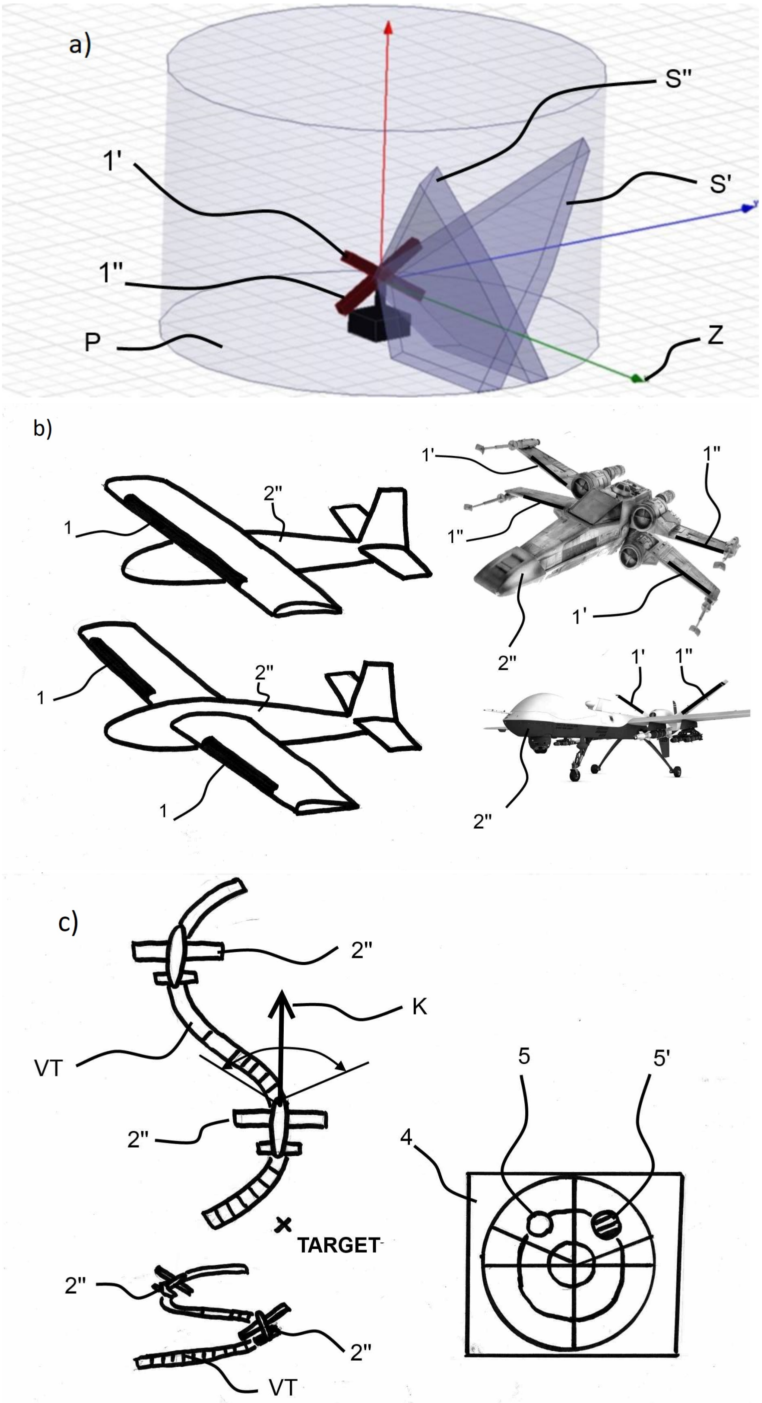

Figure 2. (**a**). Explanation of 3D radar using two inclined fan-beams, (**b**). Arrangement of the radar antennas 1 in the aircraft 2″ for the scanning by changing vehicle's trajectory VT and roll (left), arrangement of the two inclined radar antennas 1′ and 1″ in the aircraft for electronic scanning (right), (**c**). Explanation of 3D radar scanning, using one fan-beam antenna in the aircraft.

Altitude can be measured using only one fan-beam antenna in the aircraft. To do this, the aircraft's flight trajectory should be S-shaped, changing the roll naturally, as presented in Figure 2c. Unfortunately, because the distance to the target is not constant during scanning, Equation (1) is only valid when the flying radius is much shorter than the distance to the target (angles ϕ_1, ϕ_2–the scanning plane (fan beam) deviation from the vertical, γ-the angle between scanning beams OC and PD in Figure 3). Nevertheless, it is possible to calculate the altitude of the target when the positions and rolls of the aircraft and distances to the target during detection are known. To derive a more accurate expression authors will take this into consideration, as depicted in Figure 3.

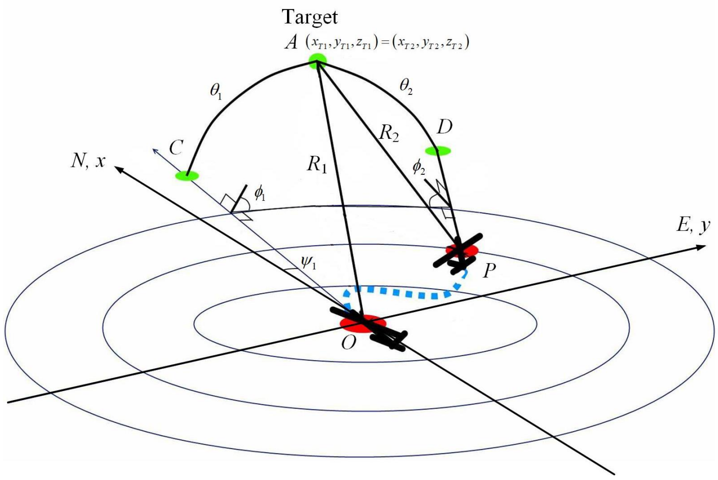

Figure 3. Three-3D radar and target plane.

We consider a scenario where the radar detects the target when the UAV is in point O, and the heading is in line OC. The distance to the target is R_1, and the false coordinates are in the point C. Because of the wide scanning beam, the exact position of the target can be in the plane COA at the distance R_1 from point O. The angle ϕ_1 between the scanning and horizontal planes depends on the bank of the UAV. The next detection of the target is found when the UAV is in point P, the heading is in the line PD, and the measured distance to the target is R_2, so the false coordinates of the target are found in point D. The scanning plane DPA and the horizontal plane form an angle ϕ_2. In this case, the exact target coordinates in point A could be expressed from the first and second scans (2):

$$\begin{aligned}
x_{T1} &= X_1 + R_1(\cos\theta_1 \cos\psi_1 - \sin\theta_1 \cos\phi_1 \sin\psi_1), \\
y_{T1} &= Y_1 + R_1(\cos\theta_1 \sin\psi_1 + \sin\theta_1 \cos\phi_1 \cos\psi_1), \\
z_{T1} &= Z_1 + R_1 \sin\theta_1 \sin\phi_1, \\
x_{T2} &= X_2 + R_2(\cos\theta_2 \cos\psi_2 - \sin\theta_2 \cos\phi_2 \sin\psi_2), \\
y_{T2} &= Y_2 + R_2(\cos\theta_2 \sin\psi_2 + \sin\theta_2 \cos\phi_2 \cos\psi_2), \\
z_{T2} &= Z_2 + R_2 \sin\theta_2 \sin\phi_2.
\end{aligned} \tag{2}$$

Here, (X_1, Y_1, Z_1), (X_2, Y_2, Z_2) are the coordinates of the UAV during the first and second scans provided by GPS RTK receiver (X–North, Y–East, Z–Height); R_1, R_2 are the distance to the target obtained from the radar, ψ_1, ψ_2 are the heading of the UAV in the moment of receiving the response from the targets during the first and second scans; ϕ_1, ϕ_2 are the scanning plane (fan beam) deviation from the vertical, orthogonal to the UAV body plane, which can be obtained from the bank angle $\phi_{1,2} = 90^\circ - \phi_{UAV}$; θ_1, θ_2 are the angle to the target in the scanning plane from the horizontal axis (intersection line of horizontal and scanning planes).

If the target is in the fixed position $(x_{T1}, y_{T1}, z_{T1}) = (x_{T2}, y_{T2}, z_{T2})$, then the two unknown angles θ_1 and θ_2—i. q. the exact target coordinates—can be calculated using the system of six equations above (2). Disturbances which are present during flight might make these equations unsolvable. In that case, an optimization task, defined by the expression (3), arises to find the minimum available distance between the two points $T1$ and $T2$, which were calculated using Equations (2):

$$\min\ d(\theta_1, \theta_2) = ((x_{T2} - x_{T1})^2 + (y_{T2} - y_{T1})^2 + (z_{T2} - z_{T1})^2)^{\frac{1}{2}}. \tag{3}$$

3. Experimental Setup

The general idea of the implementation of an airborne drone detection-neutralizing system is to utilize two UAVs: a fixed-wing unmanned vehicle with an airborne radar for hostile UAV detection, and a small "parasite" drone, which is carried by the first UAV and is equipped to neutralize the target drone.

The basic idea of the development is the embedding of the equipment in a comparatively small fixed-wing UAV vehicle with a maximal takeoff mass of no more than 25 kg. Such takeoff weight allows the implementation of UAVs with minimal legal requirements (UAVs above 25 kg must be certified according to different requirements). The main issue with fitting the UAV with the equipment is the embedding of the radar antenna, which is large, bulky and does not fit the small UAV construction too well, therefore more commonly implemented on large UAVs. The designed and manufactured fixed-wing UAV is presented in Figure 4.

Figure 4. Developed fixed-wing UAV.

As was mentioned before, the radar antenna in our case is embedded into the wing of the UAV, with scanning performed by manoeuvring the entire vehicle as shown in Figure 1.

The UAV wing was designed with special (high thickness) FX76GAP airfoil inclusion. The radar antenna is installed in front of the main spar of the wing (Figures 5 and 6) to decrease the influence of the spar material reflection on the radar data. The leading edge of the wing (in front of the radar antenna) is manufactured of high-density foam covered with three layers of 80 g/sq.m glass fibre composite, again to decrease the influence of the structure on the radar data to a minimum.

The aircraft constructed is a 25 kg maximum takeoff mass fixed wing composite UAV with a 3 m wingspan, based on a heavily modified commercial "Mugin" frame. The modifications included: a completely new wing (with the radar); a new wing mounting system; a completely new landing gear; heavily strengthened and modified fuselage of the aircraft. The wing was mounted way above the fuselage to decrease the effect of fuselage reflection on the radar data, which was detected during previous tests with the lower mounted wing, therefore completely new mounting of the wing was designed and manufactured.

The aircraft is powered by a brushless electrical motor to decrease the complexity of the system and ensure simpler testing (though limiting the endurance to 30–45 min), with the idea of replacing the electrical motor with a piston one in the near future, to ensure longer endurance. The aircraft is autonomously controlled by the "Pixhawk Cube" open source autopilot with the ArduPilot software and MissionPlanner ground station software. The aircraft with the radar system was flight tested in multiple airfields to obtain the most accurate data on both UAV and radar performance (Figure 7).

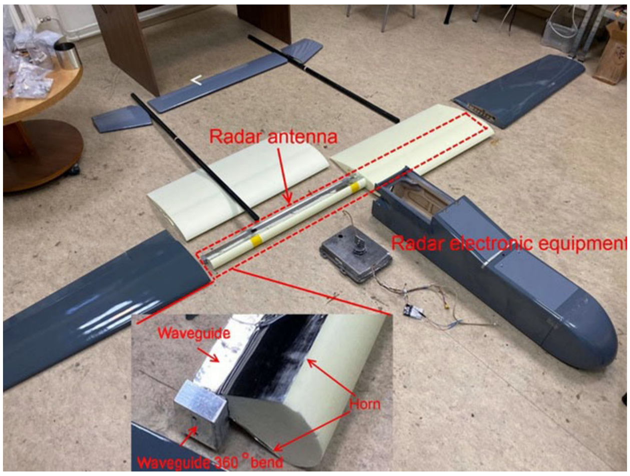

Figure 5. Embedding of a radar antenna into the fixed-wing UAV.

Figure 6. Band of reflective vinyl film on the underside of the wing.

Figure 7. Fixed-wing UAV during a mission.

A key component is a fan-beam antenna. To have better accuracy, the beam width of an antenna should be as narrow as possible. The beam width depends on the antenna width. For example, the beam width of a marine 2 m open antenna array is 1.5°. The weight without the pedestal is approximately 7 kg and the height is 10 cm.

Such an antenna is too heavy and too thick to be embedded into the wing of a small UAV. On the other hand, it is a mass-produced and relatively low-cost antenna made from aluminium. The authors designed their own antenna and used components such as a slotted waveguide and a feeding waveguide. To reduce weight and thickness (thickness of wing foil is 5 cm), we removed the radome and horn plates. As for the horn, we made a smaller horn-shaped foamed polystyrene body (Figure 5) and applied glossy self-adhesive metalized vinyl film (Figure 6). As an alternative to vinyl film, an aluminium foil can be used, but the film is lighter and more convenient to use. The electric properties of some metal shining vinyl films are similar to those of aluminium foil.

The weight of our 2 m wide radar antenna is 950 g. Due to reduced height, the radiation pattern in the vertical plane will be wider than one of the typical commercial marine radar antenna. Despite radiation in the vertical plane being changed, the horizontal structure of an antenna remains as original. Thus, the authors do not expect changes in the radiation patterns in the horizontal plane. In order to estimate the antenna radiation patterns in the vertical planes, the authors decided to make a simulation using the Ansoft HFSS software. Since the radiation pattern in a vertical plane does not depend on the width of an antenna, the authors made simulations only for the two-slot antenna cases. Due to the dielectric permittivity of foam-polystyrene material being close to $\varepsilon = 1$ and the fibreglass shell of the wing being very thin (0.4 mm), the dielectric properties of the material were not taken into account in simulations. In this paper, the authors present only general information about the used antenna. Antenna model simulation results are shown in Figure 8.

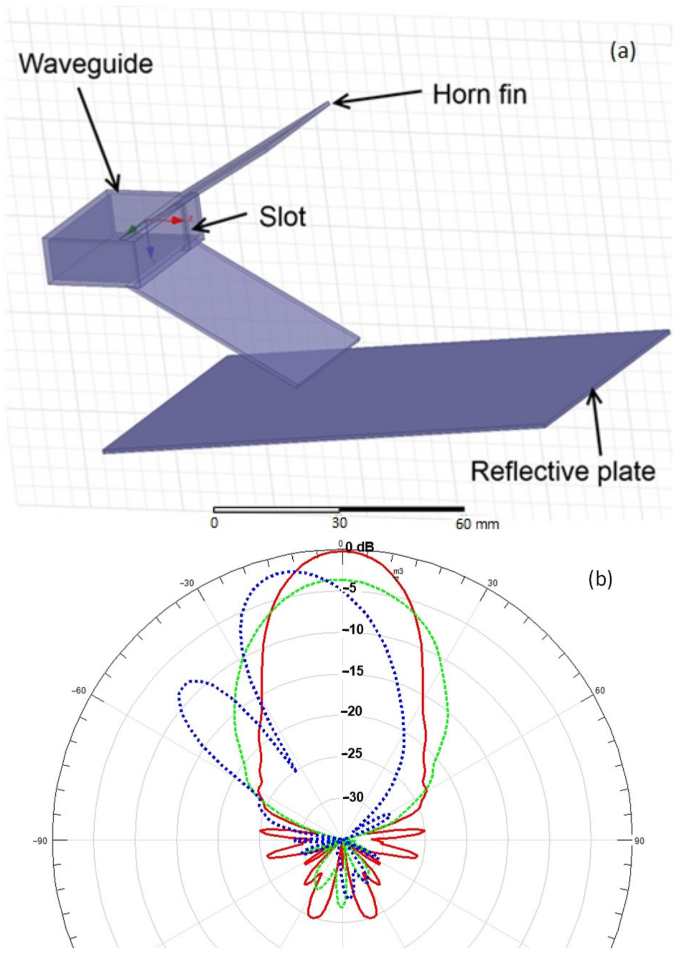

Figure 8. UAV horn antenna array. (**a**). A 3D structure model and a model of an antenna in the Ansys HFSS software, (**b**). A simulated radiation pattern (total directivity) in the vertical plane. Solid line—reference marine radar antenna; dashed line—UAV antenna with reduced height; dotted line—UAV antenna with an additional plate.

Naturally, because the height of an antenna was halved, we obtain half of the power gain and a wider beam in the vertical plane. For airborne UAV detection, a wider beam leads to a higher clutter response. By using some reflective plate below the horn aperture, we can expect lower radiation downwards. This case can be implemented very easily by sticking a self-adhesive vinyl film band on the lower side of the wing as presented in Figure 6. Depending on the application, for example, for ground observation, vinyl film can be removed from the lower side of the wing and applied to the upper side.

When using radar scanning by changing the direction of flight (Figure 1), it is important to have adequate heading information. Unfortunately, finding the heading by analysing positions from GNSS possessed by aircraft is not a good solution. In the presence of the side wind, the direction of the axis of the aircraft (heading, yaw) and the direction of flight (course or bearing) are not the same directions. To find the heading of the UAV we used two GNSS RTK receivers at the ends of the wing and the magnetic sensor was supplementary.

4. Experimental Results

During the experiments, the aim was to test the proposed radar and drone neutralization tool for the proposed UAV countermeasure platform. Starting with the radar test, the first experiment with the radar together with the constructed antenna was tested using a typical multirotor craft drone instead of a fixed-wing aircraft. The authors believe that this is a simple solution and thus this is not described in the experimental setup. In this way, it was checked whether the radar is working at all, and it was also easy to rotate the drone around its axis at a constant speed.

During this test, the drone with the radar was rotated at an angle of 160 degrees, as the aim was to detect targets in the sea. At the same time, a secondary AIS radar system was integrated into the drone, which was designed to detect targets at sea. The difference from the work [17] is that radar electronic equipment with modified 2 m width open array antenna and scanning by changing bearing of UAV was used. Therefore, the authors additionally aimed to observe whether the interferences that were seen in the recent work in the case of use will appear. Measurement was performed at an altitude of 50 m.

The obtained scanning data of both radars are presented in Figure 9. The data are aligned by taking the coordinates of the AIS targets with the geographic map and merging together with the radar image, before subtracting the background from the image.

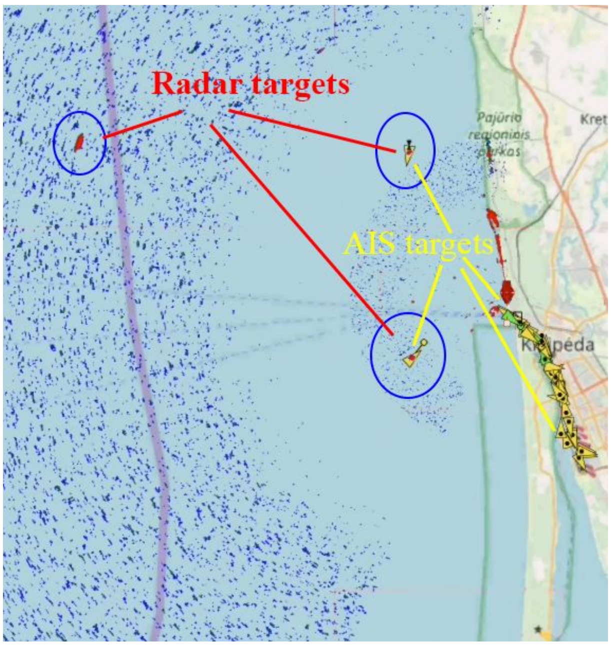

Figure 9. Composed data images from primary and secondary UAV arranged radars.

As a result, it can be seen that the data obtained from the developed radar and the AIS system exactly match after their images are combined. A small target spot on the received radar indicates that the antenna has high resolution and directivity. Along with the drone, a wing with an integrated radar and GPS RTK was lifted. Using the GPS RTK the authors got accurate coordinate measurements for the scanning system to determine antenna heading. During the experiment, the drone was hovering and did not move in space during scanning to attain accurate results.

From the obtained results we can see that the used radar did not receive any additional clearly identifiable specific noises. Only the noisy circles appeared due to the stitching of the radar's response to chirped pulses of various duration.

In the case of fixed-wing UAVs, radar response chart plotting is different than in hovering UAV cases. There is no fixed centre of the chart. A radar plot chart that was made using the OpenCPN software while scanning during a circular trajectory flight is presented in Figure 10.

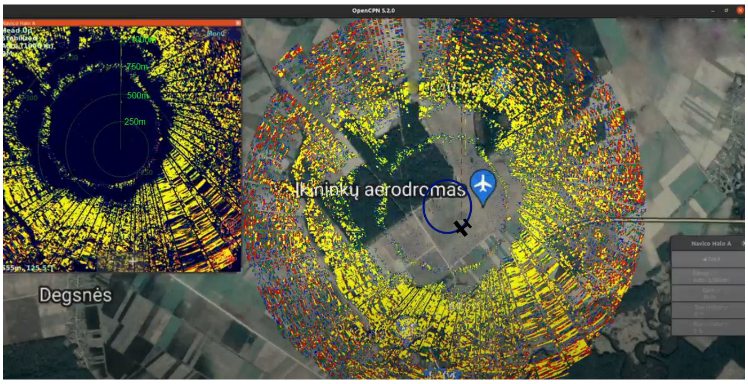

Figure 10. Clutter estimation during a flight on a circular trajectory.

Figure 10 shows some issues with the initial fixed-wing UAV flight. Here, the antenna embedded in the wing was without a reflective sticker on the wing. Due to technical issues such as some data loss, we have imperfections in the radar image.

In an additional experiment with an added reflective sticker to the wing, the authors got much better results than shown in Figure 11. Authors could provide a hovering drone for the detection and it was detected in the range of 250 m. The radar data provided accurate detection of the drone at an altitude of 50 m. Fixed-wing UAV flight altitude was at 150 m and in a continuous circle route.

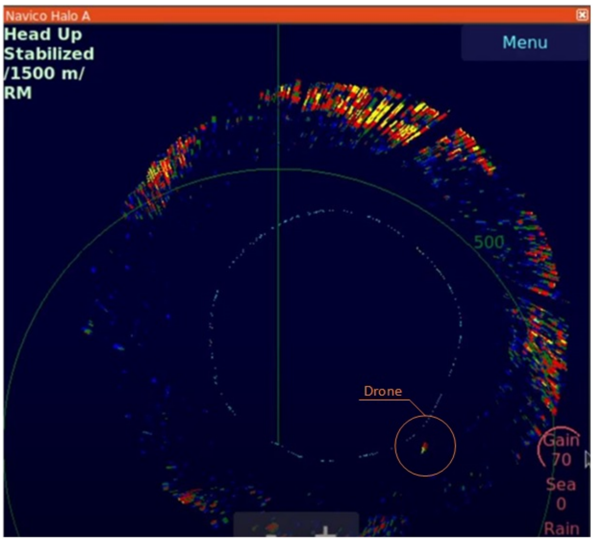

Figure 11. Detected drone using fixed-wing UAV radar.

Next, the proposed countermeasure platform experiment was related to the system of launching a "hunter" drone. To neutralize the hostile drones or fixed-wing UAVs, an additional system (which can be installed on the same vehicle) is implemented. The neutralization of the hostile drone is performed by a small rotorcraft UAV ("hunter" drone) carried on the main fixed-wing UAV vehicle to ensure endurance and range, and is launched in the vicinity of the hostile UAV (Figure 12).

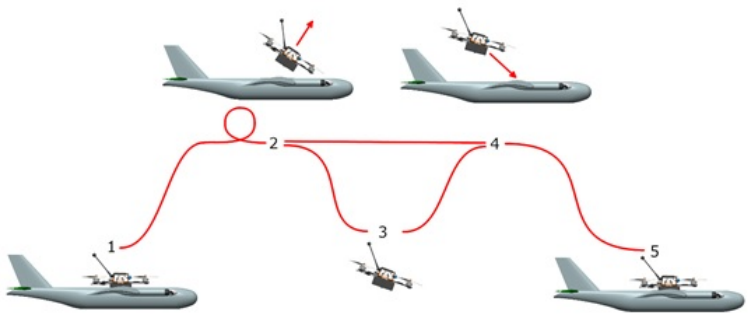

Figure 12. Launch of the "hunter" drone: 1—fixed wing carrier UAV with the drone on it; 2—drone takes off the carrier UAV; 3—drone performs its mission on its own; 4—drone lands back on the carrier UAV; 5—carrier UAV continues mission with the drone on it.

As it is widely known, fixed-wing UAVs ensure long endurance, long range and high speed of flight, due to higher efficiency of lift generation; meanwhile, rotorcraft UAVs (multirotor drones) ensure much higher manoeuvrability and agility though sacrificing the endurance and range. To ensure the combination of those two for hostile UAV neutralization the "piggyback" UAV system was developed. The system is composed of a fixed-wing UAV (in this case "Spartan" UAV vehicle manufactured by the company "Žvelk Aukščiau" was implemented as a test vehicle) ensuring long endurance of up to 3 h and a long range of up to 100 km with the piggyback "parasite" drone mounted on it (Figure 12). The parasite "hunter" drone is positioned over the centre wing of the fixed wing vehicle and held in place by an electromagnet, at the point of interception of the hostile UAV the drone is released and proceeds to the hostile UAV. In that way, the range, speed and endurance of the interceptor are ensured. The "hunter" drone is a 5-inch size racer drone-based vehicle with special modifications for the mission: a special control system; neutralizing equipment; ferromagnetic plate and others.

Launching experiments were successfully tested by implementing the modified 5-inch size racer drone and the carrier "Spartan" UAV presented in Figure 13, which is a little bit smaller than a radar-carrying UAV. In the future, it could be integrated together with a radar-carrying fixed-wing UAV or used as a separate carrier if needed.

The drone neutralizing system consists of the "hunter" drone carrying the long (2 m) tether with the parachute attached and softly packed on the "hunter" drone. The idea of the system is that while passing by the hostile UAV the "hunter" drone drags the tether through its frame and the tether gets caught by the propeller (or the air-frame) of the hostile UAV. The tether drags out the parachute and the hostile vehicle with the lost engine (due to the tangled tether) safely lands with a parachute (Figure 14). All of the experiments described were performed in manual control of a "hunter" drone, with the operator controlling the drone using FPV equipment. The fully automated target tracking is to be researched in the future.

The hunted rotorcraft drone was imitated by the 5 drone of a similar size (mass of around 1 kg), stationary hovering. The fixed-wing hunted aircraft was a commercial "Bixler" type foam airframe with full automated control, with a weight of 1.7 kg flying in an automatic circular pattern. The high speed (up to 150 km/h) and high agility of the "hunter" drone passing by the hostile UAV (even flying at comparatively high speed) does not impose a great problem (which was demonstrated in practice); therefore, the neutralizing system can be implemented, which neutralizes both fixed wing and rotorcraft vehicles.

Figure 13. Launch of the "hunter" drone.

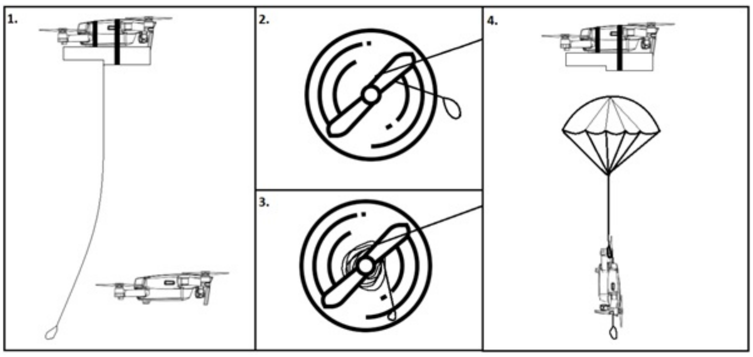

Figure 14. Principle scheme of neutralizing: 1—"hunter" drone carrying a tether (rope) to be tangled in the propeller of the hunted drone; 2—tether gets tangled by propeller; 3—tether jams the spinning of the propeller; 4—hunted drone lands with the parachute attached to the tether.

The functioning of the neutralizing system was successfully tested on both fixed-wing and rotorcraft UAVs multiple times (Figures 15 and 16). It can be stated that the neutralizing system can be implemented on UAVs with a flight speed of no more than 120 km/h. The altitude of the vehicle does not play a major role in this case.

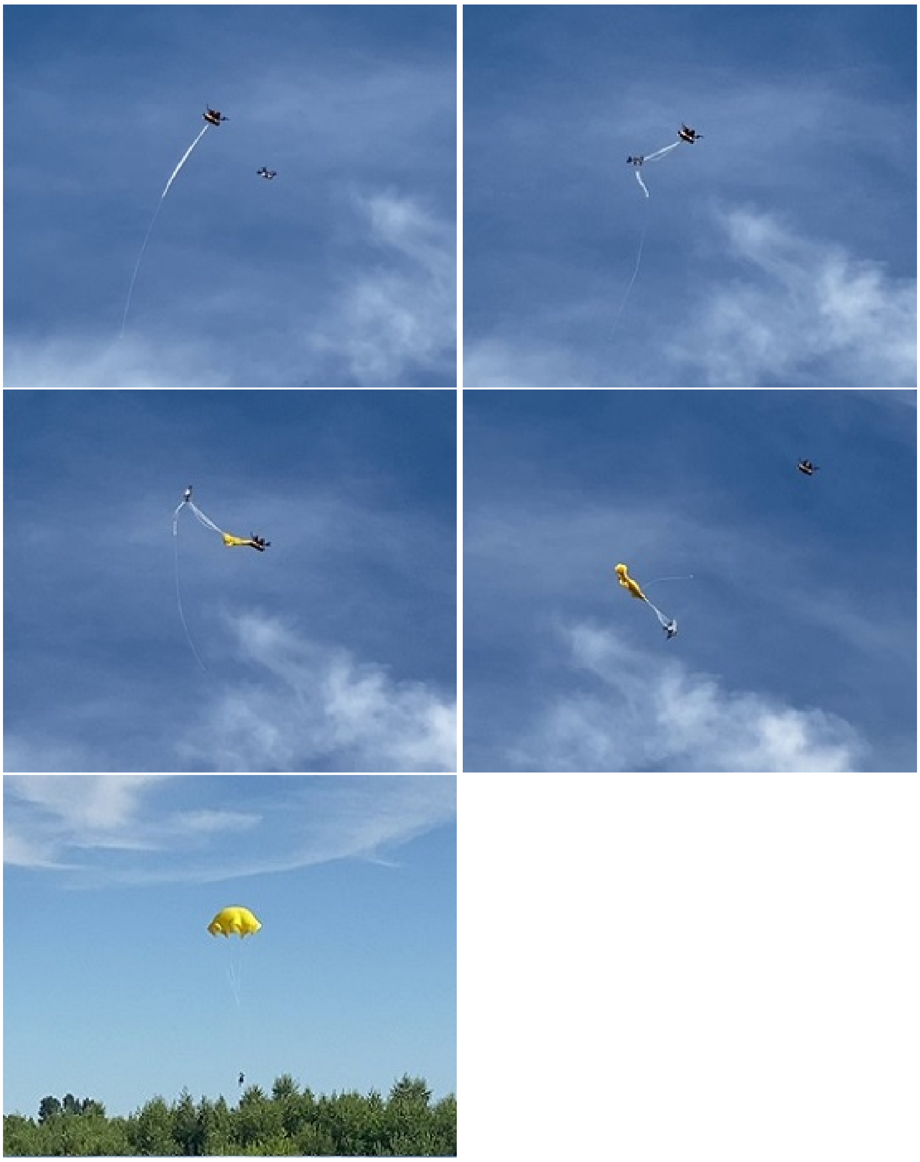

Figure 15. Neutralizing of the rotorcraft UAV.

According to the experiments, in the case of the fixed wing UAV, it is quite enough to tangle the tether into the structure of the UAV (without hitting the propeller). Due to the drag of the tether parachute, the hostile UAV loses control, stalls and lands with the parachute even with a working engine. Nonetheless, additional experiments should be performed researching the possibility of evasive manoeuvres by hostile vehicles, or the probability of catching it.

Summarizing the mentioned, the full functioning of the platform consists of:

- Detecting of the hostile drone by the airborne radar installed into the fixed wing UAV;
- Flying close to the hostile drone by the fixed wing UAV carrying "hunter" drone (that can be the radar UAV);
- Launching of "hunter" drone;
- "hunter" drone drags the tether along the hostile UAV;
- Hostile UAV gets tangled in the tether and safely lands with a parachute.

Figure 16. Neutralizing of the fixed-wing UAV.

5. Discussion

This paper presents the first results obtained during the development of the UAV countermeasure platform. The experiments carried out in the work aim to make sure that, with the implemented radar integrated into the unmanned aircraft and the developed mathematical solution, it is possible to simulate the operation of a conventional radar and detect drones. The radar embedded into the fixed wing vehicle can be used for tracking other objects too, especially maritime vehicles. In this work, an idea has been developed about how it is possible to mathematically calculate the coordinates of a detected drone using the presented radar solution and also, knowing the coordinates, activate the drone neutralizing solution.

The proposed method for the target coordinates calculation works fine if the target keeps the fixed position. The position of the target has some drift and there are inaccuracies in measurements—from UAV position determination using GPS, heading and bank detection, and distance measurement error. In addition, multiple targets can be detected. The impact of these factors can be reduced by solving the proposed minimization task defined in the proposed expression (3), and multiple targets or critical errors can be identified by evaluating the obtained distance value—the defined maximal drift should not be exceeded. Different methods of solving the minimization task can be used, and the next part of the research is to find the most effective approach. Following the previous experience, the direct search methods have great potential, particularly the simplex search. The modification of a classical Nelder–Mead method makes use of regular simplex conversely deformation to keep stable results under simple calculation actions. Further research should find the optimal trajectory of the flight to speed-up detection and increase the number of measurements to determine the movement of the target.

The idea of removing the radar rotation mechanism and embedding the antenna in the aircraft body allows us to significantly reduce the mass of the radar and increase the width (resolution) of the antenna. Very good resolution can also be obtained with SAR radars, but they usually cannot transmit images in real-time and scan in the direction perpendicular to the movement of the aircraft. This is not always convenient, as one is usually flying towards an area of interest and it is desirable to receive information as one approaches that area. In this sense, forward-looking radars are more convenient. The realization of the concept would open many possibilities for the application of an airborne radar. Although we focus more on anti-UAV, the radar can also be used for land surveillance. It is especially convenient to do this above the water surface using low-cost marine radars. It is possible to use such a UAV together with an AIS system to identify vessels in the fight against illegal migration, fishing, piracy, and smuggling. It is possible to observe ice, garbage or pollutants. Since the scanning is relatively slow, large data streams are not required to transmit the radar image–it is possible to limit yourself to tens of kbps and use a satellite connection beyond a direct line of sight.

The concept of slanted beams can be used not only when scanning when changing the direction of flight but also when using X- or V-shaped antennas (if this is possible on the aircraft). In this case, electrical scanning should be used. It is understood that the concept also applies to ground-based radars. We can use X-shaped rotating cross antennas. Then the calculation of the altitude is simplified.

The main disadvantage of this 3D radar concept is the difficulty in separating targets against the ground background or distinguishing targets from many other targets. Artificial intelligence could be used for this purpose. After scanning with two oblique beams, if the target is above the radar, we receive two responses—left and right. The higher the height, the greater the distance between not polar but Cartesian plot responses. Probably, separation of the target from the background and determining its height can be performed visually using natural intelligence. This would require the responses of different beams to be fed to different eyes in a stereo imaging system. Perhaps stereo image processing algorithms can be applied.

When the antenna is integrated into the aircraft wing, we can modify the directivity pattern of the antenna in the vertical plane by attaching a reflecting plane to the wing. Technically, it is most convenient to do this by applying a cheap vinyl reflective film. It is possible to direct the beam up or down, depending on the application area. When the next application occurs, it is easy to remove the film and apply a new one.

The proposed system of UAV neutralization has a huge advantage of comprising both the range and endurance of fixed wing UAV vehicles with agility, speed and low price of small rotor-craft UAVs. The same principle of rotor-craft UAV implementation could potentially be used for multiple other tasks such as precise surveillance by the small rotor-crafts over very long distances; small very precise payload deliveries over very long distances; neutralizing of small manned vehicles etc.

Naturally, the proposed system has certain disadvantages such as increased drag of the fixed wing vehicle due to the presence of rotor-craft on it; very complicated recovery of rotor-craft (landing on the moving and manoeuvring object). For long-range data transmission, it is needed to have special equipment or transmission nodes and, finally, control issues of the small UAV. So far, the "hunter" drone has been controlled in stabilized manual mode which requires a highly trained UAV pilot. Nonetheless, these issues are to be addressed during further steps of development which should include the implementation of automated visual target detection, automated "hunter" drone control with possible external data processing (due to the very small size of the drone itself) etc.

Precise research on the catching of hostile drone probability was not in the scope of this work, the main focus was on the proof of concept, and further research will follow. Nonetheless, according to the experiments performed it might be stated:

- The UAV vehicles flying at the speed of up to 120 km/h can be caught;
- Altitude of the target vehicle does not play a major role in catching;
- Evasive manoeuvres by the hostile vehicle were not considered, since it was assumed that the interception should take place at long distances without the hostile drone operator physically observing the action, i.e., hostile drone being controlled in automatic mode or over FPV;
- From the number of experiments which were performed, for the moment it might be stated that is takes 2–3 tries to catch the hostile drone (though those results are preliminary).

The number of drones detected by the radar is not limited by any means. The detection of the drone or a fixed vehicle detection is analysed in detail (by the same authors) in the paper [17].

6. Conclusions

Radar is integrated into the fixed wing UAV to reduce the weight, size, increase endurance etc. The vehicle with the radar is supposed to have long range, long endurance and high speed. Agility is not an important issue in this case. It requires the use of scanning by changing the direction of flight. Furthermore, in order to detect drones using the created platform, a mathematical model is derived that allows the calculation of the exact coordinates of the detected object in a three-dimensional environment.

Our lightweight solution where the radar's antenna is embedded into the wing provides the following benefits:

- Wide area of application–can be used for UAV detection, authentication of vessels (illegal migration, anti-piracy monitoring), and ice or oil spill monitoring in real-time;
- Possibility of launching from the vessel;
- Higher operational range–due to lighter weight and the better aerodynamics of wing with embedded antenna solution;
- Loose legal requirements–due to the low weight of UAV;
- It is possible to use UAVs up to 25 kg mass;
- Low price of equipment–due to usage of mass production radars and lighter weight of the UAV;
- Low operational costs–due to small dimensions, no manned flights, low fuel consumption, and simple equipment.
- Possibility of 3D scanning–due to scanning using inclined fan beams. This concept can be used not only in UAVs but also in stationary ground radars. Using marine radars is most effective in low-clutter conditions.

For the physical neutralizing of the hostile UAVs, agility is critical. Therefore, for the final part of the mission—the physical neutralization of the hostile UAV—a small multirotor vehicle (carrying catching equipment) is used. This multirotor vehicle does not carry any radar.

The obtained results show that the created platform performs the intended task of detecting a drone, determining the coordinates of the detected drone and neutralizing the detected drone or other fixed-wing UAV using the "hunter" drone.

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