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The Ground Station for Long-Range Monitoring, Flight Control, And Operational Data Telemetry of Unmanned Aerial Vehicles

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Abstract *The rapid advancement of technology in the field of unmanned aerial vehicles (UAVs) has created new possibilities for their application in numerous fields. For every unmanned aerial system it is essential to contain a ground control station (GCS), which must comply with mission-specific requirements. This paper presents the results of our research on optimizing the hardware and software components of radio communication for an UAV prototype with hybrid propulsion and integrating them into one comprehensive control station, enabling long-range operation and universal applicability to other unmanned aircraft. Our approach includes a unique solution to separate flight control from propulsion unit monitoring due to the experimental nature of the propulsion system. Flight safety was also enhanced by equipping the GCS with a system that provides information about nearby air traffic and secures the operational area against unauthorized UAV flights. Our system is capable of detecting intruders and determining their location based on intercepting UAV radio signals. Additionally, we conducted research on radio jamming as a means of interrupting the flight of a UAV that is violating a restricted airspace. Overall, our research provides insights and recommendations for the development of effective and user-friendly GCSs for UAV systems, addressing the critical need for safe and secure UAV operations.*

Keywords *unmanned aircraft, UAV, ground control station, radio communication, long range, UAV detection, radio direction-finding*

1 INTRODUCTION

The ground control station is an essential part of every existing unmanned aerial system (UAS), where its main role is providing operator with means of control, flight monitoring and most importantly radio communication. Each ground control station must comply with requirements of a given unmanned aerial vehicle (UAV) according to its purpose, capabilities and goals of a mission. In most cases, a simple compact controller equipped with screen for displaying video feed and basic flight data (altitude, position, attitude, speed, etc.) is fully sufficient. Most commercially available drones are controlled by such simple ground stations, however more demanding industrial and military UAV applications often require far more complex control stations. The long-range hybrid propulsion UAV, which is being currently developed at our department, has very specific needs for command-and-control system – ability to perform long-range missions, monitoring experimental hybrid propulsion unit (including operational data-logging), transmit

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live first-person view video footage, be capable of automatic waypoint missions and provide the operator with all needed flight data in real time. Additionally, to increase flight operations safety, a system providing the operator with information on surrounding air traffic was proposed, for monitoring both manned and unmanned aircraft. As airspace incursions by an unauthorized UAVs are becoming increasingly frequent, it was decided to also conduct research on the available means of flight termination of hostile UAVs. There is currently no complete system capable of fulfilling all of those needs on today's market, therefore it was necessary to optimize required components and also custom-build some of the systems. Emphasis was put on joining all the subsystems into one complex control station with high level of automation and user-friendly interface, therefore minimizing operator's workload.

2 CURRENT STATE OF GROUND CONTROL SYSTEMS

UAS control station is a very broad term, as there is a wide range of different types of unmanned aircraft intended for several sectors and various applications that place diverse requirements on control stations. According to the purpose of use, we can divide UAS into three main sectors:

- military and security,
- commercial,
- recreational.

2.1 Military and security sector

Like other technologies, drones also have their roots in the military sector, where the representation of various types of UAVs is still very significant. They are used here primarily for special combat or reconnaissance purposes, while they are often very complex vehicles with long range capabilities. These factors place extremely high demands on their control stations, which usually represent an entire dedicated room manned with several operators and have advanced technological and communication equipment.

2.2 Recreational sector

The recreational sector also has a relatively long tradition, while in its beginnings it was made up exclusively of model aircraft enthusiasts and their radio-controlled models with only basic flight control functions and a virtually non-existent flight monitoring system by default. In the past years, mainly due to the development of quadcopters (their affordability and ease of operation), this sector has expanded significantly to include the general public. These recreational drones have a wide range of technological capabilities, such as flight stabilization, automatic flight along a predefined route, real-time HD video transmission, relatively long range and automatic return to the take-off point. Control stations in this sector are typically found in the form of a compact controller with integrated required flight control and monitoring functions. The simplest solution is the use of a standard RC transmitter with a certain number of controlled channels and sometimes the possibility of telemetric transmission of some crucial data, for example the voltage of the on-board battery. This solution is typical for radio-controlled flying models. Complete commercial UAS intended for the general public, on the other hand, are characterized by compact controllers combining control, flight data monitoring and real-time video display.

2.3 Commercial sector

The commercial sector, like the previous ones, is also characterized by great variability with regard to the wide range of UAV applications. Commercial use cases of unmanned technologies include, but are not limited to, aerial photography, videography, photogrammetry, patrolling, mapping, infrastructure inspection, spraying, and transportation services. A control station for a commercial UAV therefore depends entirely on the specific application and can be anything from compact controllers to large and complex systems managed by multiple operators, almost always emphasizing system mobility due to the nature of aerial work.

2.4 Analysis conclusion

From the analysis of the current state of technology in the field of UAV control and the implementation of ground stations, it is clear that unmanned technologies have advanced rapidly in recent times, and a large number of ready-made commercial solutions are available on the market. However, when designing new UAV prototypes, there are often very specific requirements for their control stations, which creates the need to optimize commercial solutions or develop individual systems from scratch. In the case of our proposed prototype UAV with a hybrid propulsion, it is possible to provide control, telemetry and video transmission with existing commercial systems (with the possibility of further optimization), while there is no suitable available system for the solution of communication with the hybrid unit for testing purposes due to its experimental nature. Based on the conclusions drawn from the survey of the available equipment on the market, we therefore decided to implement a hybrid UAV prototype ground station by combining several commercially available systems and also supplement and improve the functionality with our own design of the communication system for the hybrid drive unit. Due to the high costs associated with commercial UAV detection systems, our own simplified system was developed, capable of detecting and approximating the location of UAVs that are using common frequency bands for communication with their GCSs. For the purpose of monitoring the surrounding air traffic, an already existing procedure based on an SDR receiver and ADS-B system was used.

3 LONG-RANGE RADIO COMMUNICATION

When creating a reliable long-range radio communication system, many things must be taken into consideration. Quality of radio communication is dependent on many factors, such as frequency, polarization, transmitted power, receiver sensitivity, environment, obstacles, weather and many more. Factors such as frequency and transmitting power are legally regulated, and special license may be needed for operation of certain radio communication systems.

3.1 Frequency

First of all, propagation of electromagnetic radiation through environment is highly dependent on the frequency. Lower frequency radio waves are able to easily penetrate obstacles (or propagate via reflections), while higher frequencies generally require direct line of sight between transmitter and receiver to be able to communicate. (InfiNet Wireless, 2001) Higher frequencies are however able to transmit greater amount of data in given time (have greater transmission speed), therefore a compromise must be made when deciding on used frequency. We must take into consideration compatibility with existing radio systems, band separation from possible sources of interference, available hardware components, and mainly local legislation, conditions and limitations for using given radio band. For our purposes, communication systems working in frequency bands widely used in UAV were chosen.

3.2 Directional antenna

Range of a radio system can be greatly improved by implementing a high-gain directional antenna, e.g. Yagi-Uda type. Directional antennas, as opposed to omnidirectional antennas, have majority of its gain concentrated to one main direction, from which the signal is amplified the most. (InfiNet Wireless, 2001) Generally, the higher the gain, the radiation pattern is narrower and therefore more precise alignment with the other device is needed. When dealing with moving objects, such as flying UAV, some kind of automatic antenna positioning system is required.

3.3 Free-space path loss

The loss of radio signal energy in free space depends on the gain of the antennas used, the wavelength of the radiation and the distance between the receiver and the transmitter. (Friis, 1946) The relationship between these quantities is described by the Friis' equation (1):

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2, \tag{1}$$

where:

$\boldsymbol{P_r}$ = power received [1],

$\boldsymbol{P_t}$ = power radiated [1],

$\boldsymbol{G_r}$ = gain of receiving antenna [1],

$\boldsymbol{G_t}$ = gain of transmitting antenna [1],

$\boldsymbol{\lambda}$ = wavelength [m],

$\boldsymbol{d}$ = distance between transmitter and receiver [m].

This model is valid only in an ideal case, i.e. under the assumption that the distance between the receiver and the transmitter is much greater compared to the wavelength of the radiation, the transmission takes place in a vacuum, both antennas are correctly oriented to each other and have the same polarization, the antennas are located in free space without obstacles that would cause reflections or multipathing, and the bandwidth used is narrow enough that the entire transmission can be defined by one wavelength. (Friis, 1946)

3.4 Other losses

During the propagation of radio signals through the environment losses always occur, the size of which is mainly determined by the distance of the receiver from the transmitter, the physical properties of the environment, the wavelength of the signal and the antennas used. Because of these losses, the range of any radio system is limited to some extent, which of course must be taken into account in the design. In basic radio communication over shorter distances within the Earth's atmosphere, the biggest limiting factors besides the free-space path loss are:

- atmospheric absorption,
- reflections,
- multipathing,
- scattering,
- diffraction,
- refraction,
- losses within radio hardware. (Pindoria, 2019)

3.5 Theoretical calculation of the range of radio systems

Long-distance radio transmission systems can be compared with a quick theoretical calculation. In the theoretical calculation of the range, it is necessary to take into account all the mentioned factors affecting the propagation of the signal. Using the following simple equation (2), it is possible to estimate the approximate expected theoretical intensity of the received signal at the receiver (Cadence Systems, 2012):

$$P_R = P_T + G_T - L_T - FSLP + G_R - L_R - L_{Misc}\ , \tag{2}$$

where:

P_R = theoretical received power [dBm],

P_T = transmitted power [dBm],

G_T = gain of the transmitting antenna [dBi],

L_T = losses within transmitter hardware [dB],

FSLP = free-space path loss [dB],

G_R = gain of the receiving antenna [dBi],

L_R = losses within receiver hardware [dB],

L_{Misc} = miscellaneous losses [dB].

This equation adjusts the transmitted power value (expressed in dBm – decibel over a milliwatt) by subtracting various losses and adding gains of the used antennas. The losses are represented in units of dB (decibel), while the antenna gain is measured in dBi (decibel over an isotropic radiator), both of which are dimensionless ratios and therefore can be used in the same equation as the absolute power given in dBm. Because of this, the equation allows for calculating the measure of absolute received power (in dBm) by subtraction and addition of these dimensionless values, despite the seemingly different units. (Hayward, 2007) Overall, it enables evaluation of maximum theoretical received power by taking into account transmission losses and characteristics of used antennas.

Please not that this calculation is only theoretical, and is applicable only in ideal conditions. In real-world conditions the range could be only a fraction of the calculated theoretical distance. However, this method is suitable for comparing various radio communication systems, and based on such calculations the individual components for the GCS were chosen.

4 FLIGHT CONTROL AND TELEMETRY

Ability to control the flight and monitor real-time flight data is the most vital function of the entire ground station and associated radio communication equipment. The main component of the flight control section is the Pixhawk 5X flight computer, which, based on received instructions, controls the thrust of the engines and deflections of individual control surfaces using servomotors, and at the same time provides the operator with flight data gathered from integrated sensors. For communication between the ground station and the flight computer, radio telemetry modules RFD868x were chosen based on the research. Their operating frequency is 868 MHz, with a maximum power of 1 W (30 dBm) and a transmission speed of up to 500 kbps. (RFDesign, 2020) When equipped with basic omnidirectional antennas, they have a range of up to 40 km, which can be increased if necessary, by using directional antennas and preamplifiers. Control of the UAV is handled through the RadioMaster TX16S transmitter, which wirelessly transmits instructions via the S-BUS protocol to the 2.4 GHz FrSKY R-XSR receiver directly connected by cable to the ground radio module RFD868x. From there, the control instruction travels wirelessly to the on-board radio module connected to the flight computer. The latter sends back the telemetric flight data via the on-board module to the ground module connected to the main control computer. To display the flight data, the Mission Planner software (Fig. 1) is used, which can also be used for automatic flight according to predefined turning points and other advanced flight modes (return to the take-off point, waiting at a designated place, etc.).

Altitude (m) 0,00

GroundSpeed (m/s) 0,00

Dist to WP (m) 0,00

Yaw (deg) 0,00

Vertical Speed (m/s) 0,00

DistToMAV 0,00

Fig 1 User interface of the Mission Planner software; source: author

Range of the system can be further improved by implementing high-gain directional antenna on the ground station side of the system. This however creates a requirement for automatic antenna positioning system, ensuring correct orientation of the antenna to achieve maximum signal strength.

5 VIDEO TRANSMISSION

To increase situational awareness and improve the piloting experience of the operator, an onboard first-person view (FPV) camera with a real-time video feed was utilized. This subsystem uses a miniaturized FPV camera Foxeer Predator V5 Nano with a 155° field of view, 1000TVL resolution, and a standard 5,8 GHz analog video transmitter VTX AKK FX2 with a maximum transmitting power output of 1200 mW. The transmitter is equipped with an omnidirectional antenna Foxeer Pagoda Pro 5,8 GHz with circular right-hand polarization, while receiving of the signal is carried out by an RD945 receiver with a helical directional high-gain antenna. To further improve the video system’s range, the receiver is mounted on an automatic antenna tracker, which takes care of positioning the antenna on the flying UAV at all times.

6 EXPERIMENTAL PROPULSION UNIT MONITORING

Due to the experimental nature of the hybrid UAV propulsion unit, its control and monitoring has been solved with a system entirely separated from flight control and telemetry. In the early development and testing stages, this solution will make it much easier to make changes to the propulsion unit's control system and will reduce its impact on flight safety. The radio control and telemetry system of the hybrid propulsion unit consists of two almost identical, purpose-built radio modems, one located on board the UAV and the other incorporated into the ground unit. Each of the radio modems consists of a programmable microcontroller Arduino Nano Every and a 433 MHz industrial radio module AS32-TTL-100 with a peak transmitting power of 100mW and a maximum transmission speed of 600 kbps. The range of the system in the basic configuration with omnidirectional antennas is up to approximately 3 km within a line of sight, while it is also possible to increase it with directional antennas and preamplifiers. The onboard unit communicates directly with the hybrid propulsion control unit, while it can read operating data from it and send control instructions back. The ground modem is connected to the main computer's USB port, through which it communicates with a specially developed user interface. This software, created in the Python programming language, displays current operating data about the hybrid propulsion unit. In the early development phases, it is also capable to be used for direct wireless control of the hybrid unit. The program also saves all received data into a .csv file, so after the flight is completed, a detailed retrospective analysis of the operation of the drive unit during the flight is possible. Our first long-range tests proved stable connection to up to 1 500 m, without a line of sight, even through multiple buildings.

7 AIR TRAFFIC MONITORING

To increase the operational safety of the hybrid UAV, air traffic monitoring system has been implemented into the proposed GCS. The system is based on the automatic dependent surveillance broadcast (ADS-B) system, which is compulsory for all aircraft flying in high altitudes and certain airspace (Davidson, 2022), and nowadays also increasingly used amongst general aviation aircraft. The system consists of the omnidirectional 1090 MHz antenna, AIRSPY software defined radio (SDR) receiver and the main control station computer. Received signal is processed by the decoder „virtualradar", and data are displayed using software adsbSCOPE 2.7 (Fig. 2). The system is capable of detecting air traffic within a radius of approximately 200 km (depending on obstacles and altitude of the airplane) and provide various information about detected traffic (type, registration number, altitude, position, course, speed and more). Access to such information gives the operator enhanced situational awareness and mitigates risks of mid-air collision with nearby air traffic.

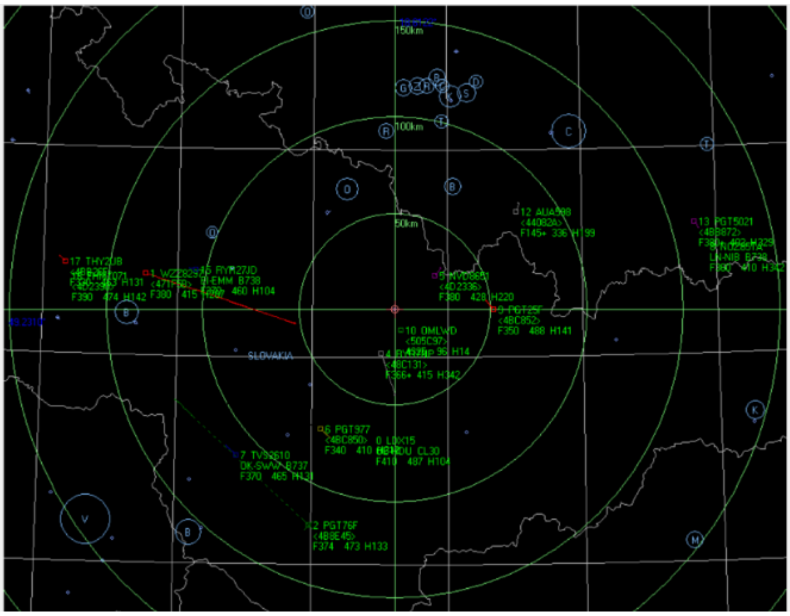


Fig 2 ADSBScope graphic user interface; Source: author

Experimental measurements were also performed to verify the functionality of the system for receiving ADS-B messages. When placing the antenna, consideration must be given to limiting the number of obstacles in all directions and the correct orientation of the antenna with respect to its polarization. The system worked as expected, the software was able to successfully pick up all ADS-B equipped aircraft in the vicinity up to a distance of approximately 250 km (depending on the flight altitude, the distance 250 km is valid for airliners in cruise). The real-time graphics software updated an overview table of the captured flight traffic and marked the aircraft in the map view as well. The size of the displayed area in the map view can be adjusted to meet operator's needs.

8 UAV DETECTION AND LOCALIZATION

To further increase operational safety, also a UAV monitoring system has been developed as a part of the ground control station.

8.1 Radiofrequency detection

Currently, we can approach the detection of unmanned vehicles using several methods, each of which is characterized by different levels of difficulty, effectiveness and brings different advantages and disadvantages. Main categories of viable detection methods are:

- Optical detection,
- Radar detection,
- Acoustic detection,
- Radiofrequency detection. (Gelman et al., 2019)

Because of its relatively high reliability, sufficient range, independence from weather conditions and good financial availability, the radiofrequency detection method has been chosen for our system. This method uses passive monitoring of frequency bands used by unmanned aerial systems (UAS) to detect the presence of UAVs in the secured area. Each unmanned aerial vehicle and its control station are equipped with radio transmitters and receivers designed for mutual communication - transmission of control instructions (C2 link), telemetry data and video in real time. By using suitable radio receivers and antennas, we are able to capture these signals and thereby detect the presence of UAVs in the monitored area. (Gelman et al., 2019) The only significant shortcoming of the radio method is its inability to capture UAVs flying in fully autonomous mode. An unmanned aircraft operated autonomously has a flight route pre-programmed in the on-board flight computer, it does not communicate with its control station in any way, and thus there are no radio signals that could be intercepted.

For its successful implementation, we primarily need a receiver with a suitable frequency range and sensitivity. Particularly suitable are the so-called broadband SDR receivers, which are characterized by limited number of hardware components and great flexibility, since, unlike traditional receivers, the processing of the received signal is handled exclusively by the software part of the system. Another important part of the detection system is the receiving antenna, which should be omnidirectional, thus ensuring the coverage of all geographical directions and also tuned to the frequencies where we expect the activity of the detected UAVs. To increase range of the system, it is possible to use an antenna preamplifier, which can be used to amplify weak signals.

The operation of the radio detection system consists in scanning certain sections of the radio frequency spectrum, in which we assume the occurrence of signals produced by unmanned vehicles. Mass-produced UAVs intended for the general public use only a few frequency bands (mainly 2,4 GHz and 5,8 GHz), but home-made and modified devices that can use various other frequencies for communication must also be taken into account. Therefore, to achieve the highest possible success rate, it is advisable to monitor the largest possible part of the radio frequency spectrum.

8.2 Radio direction-finding

To ensure better situational awareness, it is beneficial to approximate location of the detected threat. An effective way of determining the position of a UAV is radio direction-finding, which comprises of determining the direction to the radio signal source from the monitoring station. The direction-finding process is fully passive, it does not require any cooperation from the target's transmitter and detailed characteristics of the given signal are not even needed.

One of the least complicated, but highly reliable methods of radio direction-finding consists of a directional antenna placed on a rotating mechanism connected to a radio receiver capable of measuring and recording signal strength. The directional nature of the antenna will cause the intensity of the received signal to be directly dependent on the direction of rotation of the antenna relative to the radio source. At the moment when the maximum of the antenna's radiation characteristics is directed directly at the targeted source, receiver will record the maximum signal intensity, by deflecting the antenna from this direction, the signal strength will decrease. We can use this phenomenon to determine the azimuth and also the elevation angle to the radio signal source - the target. (Read, 1989)

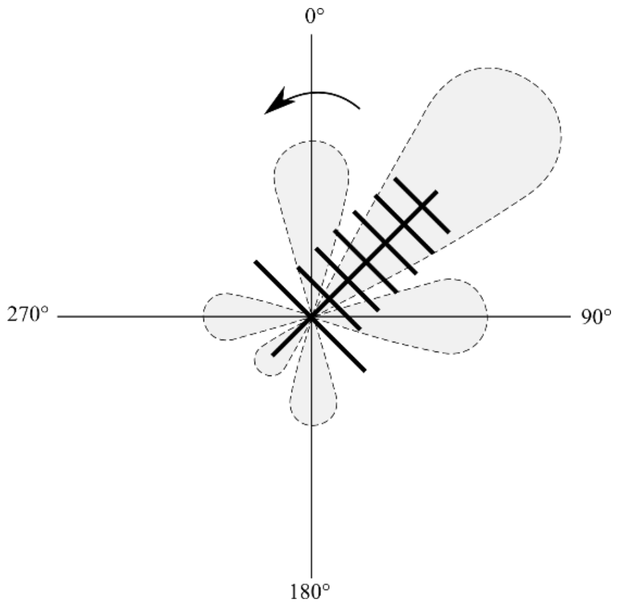


Fig 3 Rotating directional antenna with its radiation pattern; Source: author

This process was successfully automated by developing custom Python-based software solution with user-friendly GUI (graphic user interface). The GUI is capable of controlling the stepper motors which rotate the directional antenna using the Arduino microcontroller. Antenna can be moved either automatically in "scan" mode, or manually (mainly for direction calibration purposes). Signal processing is managed by HackRF SDR receiver and SDRSharp software. The operator first sets the frequency on the receiver (according to the detected signal) and initiates the antenna scanning. The antenna we have been using is the wide-band directional LogPer type with frequency range of 750 MHz – 11 GHz. Signal strength and antenna position is then automatically evaluated by the software, and operator gets real-time results of the measurement in form of easy-to-read radial chart. On the chart it is apparent in which direction is signal strength the greatest, which corresponds to the direction in which is the target located.

9 UAV RADIO JAMMING

After a successful detection and localization of an unauthorized UAV in the area of operation, the situation might demand flight termination of the intruder. There are two main ways of disabling a UAV – physical or electronic intervention. Our research was oriented on the latter, specifically on disturbing UAV's radio communications. This can be performed by either jamming its control and communication signal or disrupting GPS signals. (Matic et al., 2020) Both of these approaches have their advantages and disadvantages.

9.1 Radio communication jamming

By generating a sufficiently powerful radio signal in the frequency band, which is being used for communication of the targeted device with its control station, it is possible to disrupt this communication. If done correctly, the targeted radio link will be lost in the noise produced by the high-intensity jamming transmitter, and UAV's onboard receiver won't be able to pick out the correct signal. However, modern drones are increasingly using robust communication methods with good resistance against jamming (e. g. FHSS and DSSS modulations (Shukla et al., 2016)), which further complicates the usage of this method and demands very high transmitting power of the jamming device. It is rather difficult to predict what will happen to the intruder, as this highly depends on the UAV type, its flight computer, and fail-safe settings. The main results of successful radio jamming would be:

- UAV maintaining its last position,
- Return to the take-off location,

- Loss of control and subsequent crash.

9.2 GPS spoofing

The second, somewhat more complicated option is generating and transmitting a false GPS signal. Using a sufficiently powerful transmitter, artificially generated false signals are transmitted to the target. These are in the very same format as real GPS data packets, only with certain parts of information changed. (Ebinuma, 2015) Because of this, the GPS receiver would mistakenly consider them to be real data from GPS satellites and use them to identify its position, which would be incorrect. Based on multiple factors, the UAV could base its position entirely on the false signals or could be unable to determine the location as a result of receiving conflicting information from real satellites and the jammer. By implementing advanced algorithms into this method, a device could be developed with the capability of altering the intruder’s flight path in real-time as needed by generating suitable false GPS signals. The simpler and also safest approach utilizing this method would be manipulating the false signals in a way, that UAV would calculate its real position, however at a significantly higher altitude, which would cause its subsequent descent and ultimately landing.

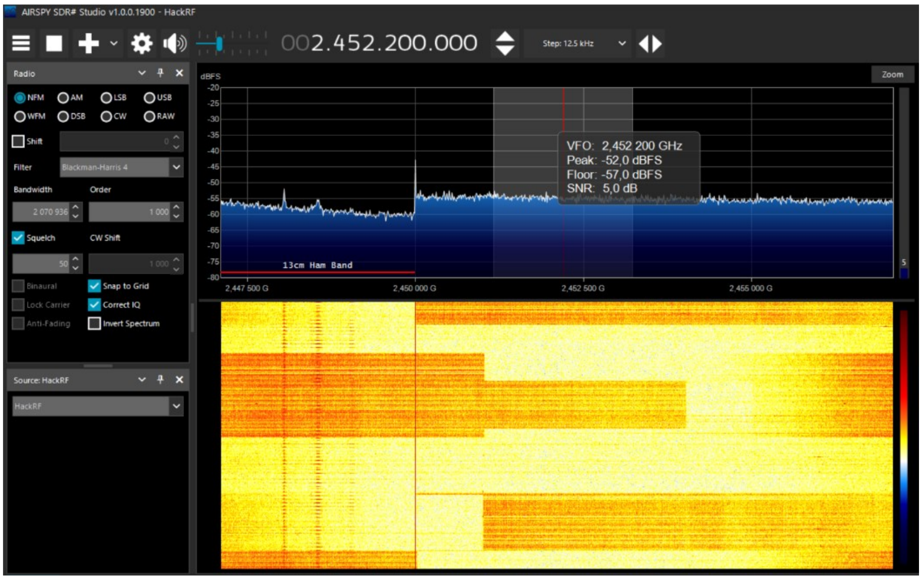
The main disadvantage of this approach is that it is affecting all GPS devices in the vicinity equally, which could cause serious safety concerns, especially when used near airports. Some UAVs could also be immune to this jamming, as they could also be using different positioning systems which wouldn’t be affected.

10 EXPERIMENTAL VERIFICATION OF THE UAV DETECTION AND LOCALIZATION SYSTEM

Thorough testing was conducted on UAV radio detection and direction-finding equipment. Experiments were focused mainly on determining the system’s range and accuracy of the direction-finding function.

10.1 Range of the UAV radio detection system

Since the easiest detectable radio transmission in UAS is video transmission, the experiments were focused on it. A HackRF One SDR receiver, identical to the receivers of the detection and targeting system, was used to measure the intensity of the received signal. The received signal intensity was measured using SDRSharp software. The signal source in the first group of experiments was a commercially available DJI Mini 2 drone, representing a typical UAV available to the general public. This group of unmanned vehicles is currently the most numerous, and is also the most frequent cause of incidents of unauthorized vehicle intrusion into prohibited or restricted airspace. The tests were performed on flat terrain with direct visual contact, while the UAV flew at a height of 40 meters above the terrain. The measuring station was stationary, the drone operator moved to places with a known pre-measured distance from the measuring station (distances measured using the Google Maps online service). Measurements were made using an omnidirectional antenna tuned for 2.4 GHz and 5.8 GHz frequencies supplemented with an LNA preamplifier. Even at a distance of 1,500 m from the receiver, the signal intensity was still 5 dBFS above the noise level (shown by the gray line), and thus the signal from this distance can be considered well detectable. (Fig. 4, Fig. 5)



AIRSPY SDR# Studio v1.0.0.1900 - HackRF

002.452.200.000

Step: 12.5 kHz

Radio

● NFM ○ AM ○ LSB ○ USB
○ WFM ○ DSB ○ CW ○ RAW

☐ Shift 0

Filter: Blackman-Harris 4

Bandwidth: 2 070 936

Order: 1 000

☑ Squelch 50

CW Shift 1 000

☐ Binaural
☐ Lock Carrier
☐ Anti-Fading
☑ Snap to Grid
☑ Correct IQ
☐ Invert Spectrum

Source: HackRF

HackRF

VFO: 2,452 200 GHz
Peak: -52,0 dBFS
Floor: -57,0 dBFS
SNR: 5,0 dB

Fig 4 Spectrogram of the signal received from DJI Mini 2 from a distance of 1 500 m; Source: author

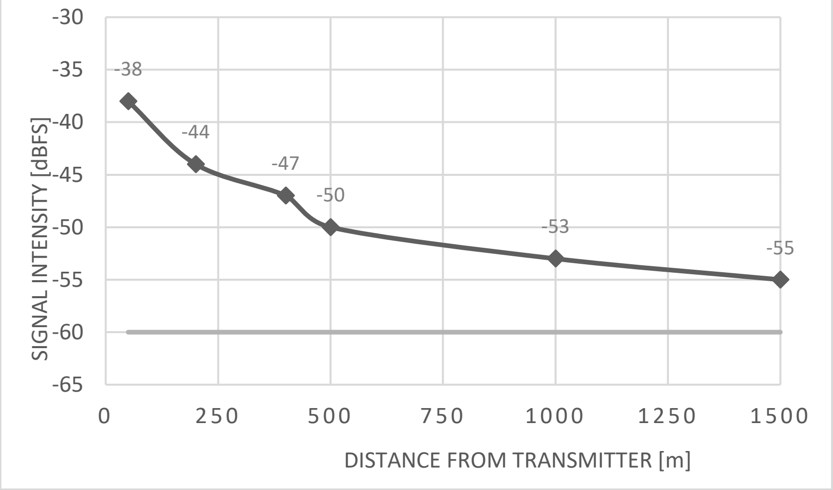


Fig 5 Intensity of the signal received from DJI Mini 2 from various distances, measured using an omnidirectional antenna and LNA; Source: author

Other measurements use an analogue 5.8 GHz FPV video transmitter as a signal source, commonly used on various homemade drones. These UAVs are not as numerous as commercially produced units, but still pose the same threat to the operation of the UAV or other secured object/activity. For practical reasons, during the measurements, this transmitter was not placed on a flying UAV, but on a 2 m high wooden mast, which was placed in flat terrain, always in direct line of sight to the detection station.

In a range test of an omnidirectional antenna with a preamplifier, the signal from the 5.8 GHz transmitter proved to be indistinguishable from noise at a distance of 750 m. At a distance of 500 m, the detection was still reliable, but in the interval of 500 - 750 m, however, it became less and less clear (Fig 6). Range of the detection system can therefore be set at a value of 500-750m. This relatively low value is the result of several factors. By their nature, higher frequencies (such as 5.8 GHz) are more susceptible to atmospheric effects and obstructions, making them less reliable for transmission over longer distances than transmission at a lower frequency with the same transmit power. In addition, the transmitter in question used the widespread "Pagoda" type antenna with circular polarization in the UAV community, while the dipole omnidirectional antenna used has linear polarization. This discrepancy causes very significant losses during signal reception, which can be solved in the future by implementing an antenna with circular polarization for better coverage of these types of transmitters.

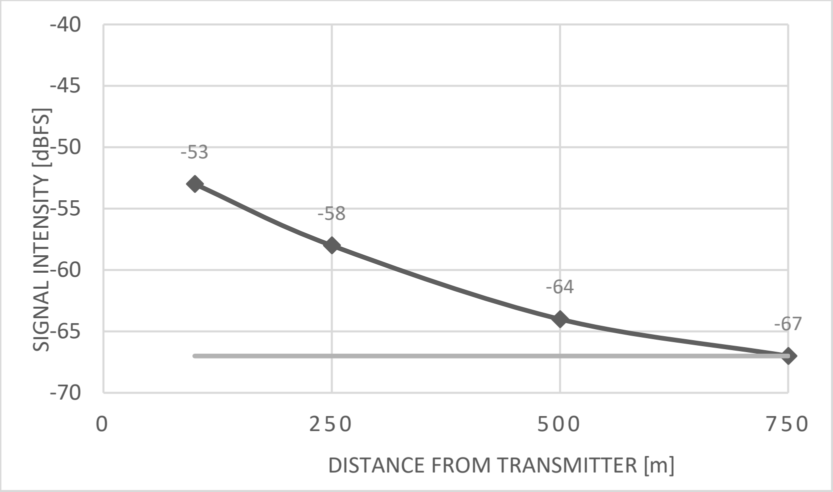


Fig 6 Intensity of the signal received from 5,8 GHz transmitter from various distances, measured using an omnidirectional antenna and LNA; Source: author

10.2 Range of the UAV direction-finding system

The second series of experiments took place with the same signal sources (DJI Mini 2 and 5,8 GHz video transmitter), but this time with a LogPer wide-band directional antenna proposed for direction-finding. In this case, the signal strength at a distance of 2 000 m was even up to 8 dBFS above the noise level (Fig 7). A directional antenna has a significantly higher gain than an omnidirectional one, and therefore achieves better long-distance performance even without an additional preamplifier. From the point of view of the functioning of the detection-aiming system as a whole, this value is not very authoritative, since the range of the detection part is the limiting factor. Radio targeting is performed only after successful detection by the omnidirectional antenna, and thus we can assume sufficient signal intensity recorded by the directional targeting antenna in all circumstances.

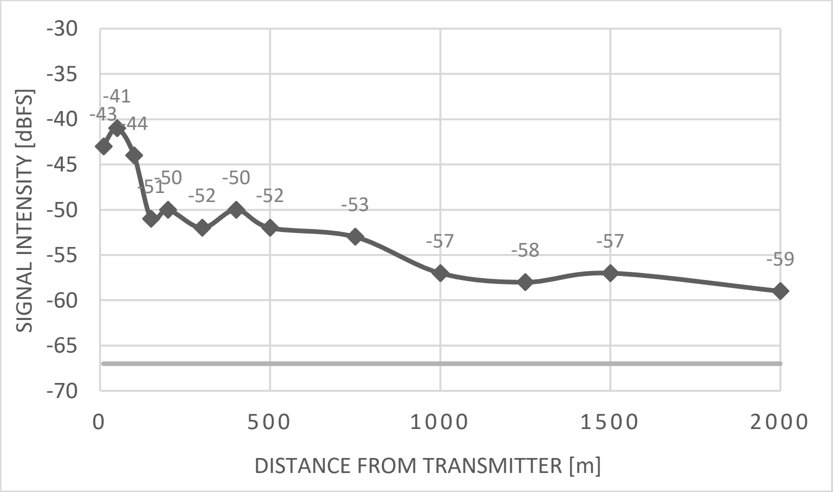


Fig 7 Intensity of the signal received from DJI Mini 2 from various distances, measured using a directional LogPer antenna; Source: author

5,8 GHz transmitter was also tested with the directional antenna. The test of the directional antenna with a 5.8 GHz transmitter produced similar results to the omnidirectional antenna. The range was slightly higher, which meets the conditions of using the targeting system after successful detection (Fig 8).

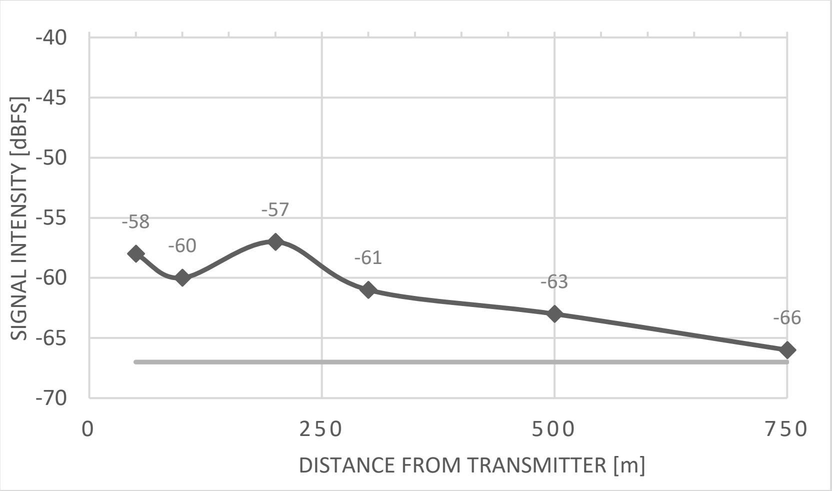


Fig 8 Intensity of the signal received from 5,8 GHz transmitter from various distances, measured using a directional LogPer antenna; Source: author

10.3 Accuracy of the direction-finding system

In order to verify the correct function of the direction-finding automation system and to determine the its accuracy, another series of experiments was conducted. The measurements were carried out using the experimental set-up consisting primarily of a directional LogPer antenna, an antenna rotation system, a HackRF SDR receiver and an automation software. The targeted UAV in these tests was a DJI Mavic flying at a height of 10 m at a distance of 30-40 meters from the ground station. By scanning the radio spectrum as part of the radio detection procedure, the frequency band of the unmanned vehicle's transmission was detected, to which the software was subsequently tuned for receiving and determining the signal intensity. The first test was performed with the antenna rotated by 90° between azimuths of 360° and 270°, while the targeted UAV was located at an azimuth of 300° to 310° from the ground station. The given graph of the dependence of received signal’s intensity on the azimuth of the antenna rotation (Fig. 9) was made from the recorded data, which were automatically saved in the form of a .csv file by the software. The orange curve shows the relative intensity of the received signal, the black is a moving average of these values with a period of 5.

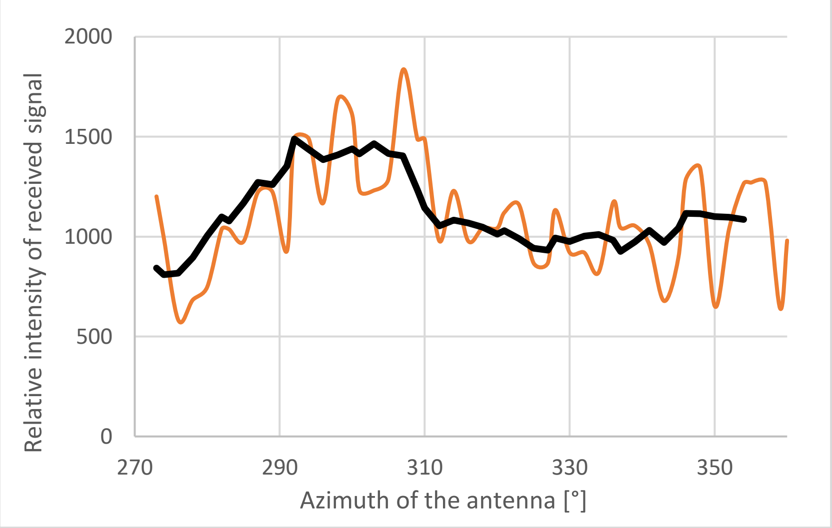


Fig 9 Relative intensity of signal received, in various directions, UAV at an azimuth of 300°; Source: author

In the next similar test, the sector was scanned from 30° to 140°, while the UAV was located at the same distance as in the previous measurement, but this time at an azimuth of 100° (Fig. 10).

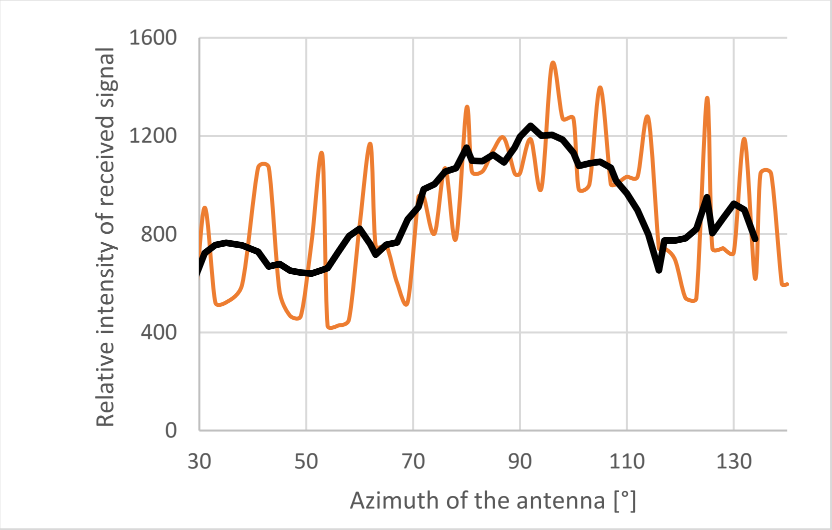
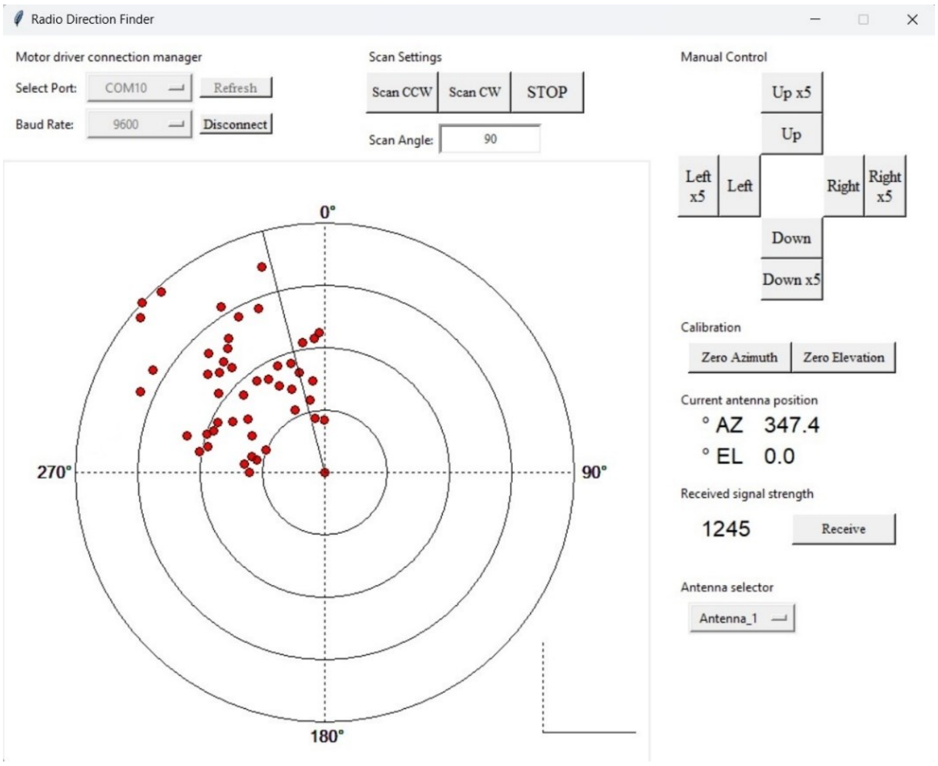


Fig 10 Relative intensity of signal received, in various directions, UAV at an azimuth of 100°; Source: author

From the graphs of the results of the experimental measurements, it follows that the accuracy of direction-finding with this system is at the level of ±10°. Achievable accuracy strongly depends on the nature of the received signal, distance and flight speed of the targeted UAV.

During the measurements, the software also displayed the actual measured values in real time using a radial graph. Thanks to this function, the operator can evaluate the position of the targeted target immediately, while performing the targeting itself. Fig. 11 illustrates the display of the first measurement in real-time, with the UAV at 310° azimuth and 270°-360° scan range.



Select Port: COM10

Baud Rate: 9600

Scan Angle: 90

Current antenna position
° AZ 347.4
° EL 0.0

Received signal strength
1245

Antenna selector
Antenna_1

Fig 11 Graphic user interface of the direction-finding software during test, UAV at 300°; Source: author

During the tests, however, a relatively large variability of the intensity of the received signal was shown, caused by the nature of the signal itself and possible imperfections of the software when evaluating the intensity of the received signal. This fluctuation of values, together with the absence of data point connecting lines, caused an ambiguous graph of the measurement results to be drawn in real time, which greatly complicated the determination of the direction to the target source by the operator. The process of automatically setting the range of the graph made this phenomenon even stronger, in the future it would be advisable to add the option of setting the display range by the user in the graphic interface. When analysing the recorded data from the measurements, we found that the use of the so-called moving average in the graphs will sufficiently highlight and smooth the course of the signal intensity. For this reason, we propose the implementation of averaging the measured values in real time, before recording the measurement results in the radial chart. This measure will improve the readability of the chart and allow the operator to determine the direction to the targeted UAV with greater accuracy and clarity.

11 CONCLUSION

The output of the research is a fully functional complex control system for UAVs with a hybrid drive, with user-friendly operational characteristics. The integration of all necessary ground systems into one comprehensive control and monitoring station (Fig. 12) ensures the simplicity of system operation and shortens the time required to prepare the UAV for deployment.

Fig 12 Completed complex ground control station during tests; Source: author

In the future, the user interface of the hybrid propulsion radio system can be supplemented with additional functions and data displays based on the needs of the hybrid unit. The primary scientific contribution of the project lies in the optimization and appropriate combination of available communication means for use in long-range UAVs. We used a non-standard configuration of up to three different types of communication means, which made it easier and safer to integrate the experimental hybrid engine into the unmanned aircraft.

Proposed systems were tested by a series of short-range experiments in real operating conditions to verify their functionality. The performed tests proved the satisfactory operability of the individual systems for the given application. Despite the fact that the designed systems in their current form already meet all the requirements of the hybrid aircraft prototype, it is possible to improve them in the future through further development and thereby increase their functionality and reliability in real operation. The main flight control and telemetry communication system has excellent characteristics in terms of range. The other radio systems on board do not have such a range, but they are not always necessary for the operation of the aircraft on long-distance automated flights, and it would be possible under certain circumstances to make a flight even without their connection. However, they are fully sufficient for all flights planned so far, and in addition, their range can be increased to a certain extent by the methods described above, as needed. The designed GCS is not limited only to this specific UAV prototype, but it was made with universal usability in mind, allowing it to be used in conjunction also with other similar unmanned aircraft.

Systems of detection and monitoring of both air traffic and other unmanned devices significantly elevates flight safety of UAV operated using the proposed comprehensive ground control station. The UAV detection and localization (specially with jamming capabilities, subject of future research) subsystems have also an ability to be operated independently from the rest of the GCS, giving them perspective to be used for protection of restricted airspaces and other critical areas.

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