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Institute of Computer Science
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Robert Raul Matsar

Feasibility of Low-cost Drone Direction Finding via Software-defined Radio

Bachelor's Thesis (9 ECTS)

Supervisor(s): Danielle Melissa Morgan, MSc

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Abstract: In this thesis, the feasibility of a low-cost solution for the direction finding of first-person view drones by their radio emissions is explored. The increased widespread use of fast-flying first-person view drones has highlighted the need for affordable detection systems to address the risks they pose, such as physical harm and privacy violations. Existing solutions to this problem are often not affordable. A mechanically-actuated scanner utilising a directional antenna and a software-defined radio device was designed for direction finding of first-person view drone video signals. Evaluation of the designed system at distances ranging from 25m to 250m showed little average error when determining the direction of a first-person view drone's video signal emissions relative to the built scanner.

Keywords: First-person View drone, Software-defined Radio, Direction finding, HackRF One

CERCS: P175 Informatics, systems theory

Tarkvarapõhise raadio abil rallidroonide taskukohase raadiolokatsiooni teostatavus

Lühikokkuvõte: Töö eesmärk oli uurida tarkvaralise raadio abil raallidroonide raadiolokatsiooni taskukohast teostatavust rallidroonide poolt välja saadetud signaalide põhjal. Rallidroonide laialdane levik ja nende poolne oht tekitada kahju nii varale kui ka inimeste tervisele ja privaatsusele, on toonud esile vajaduse tuvastussüsteemide järele. Olemasolevad lahendused ei ole sageli taskukohased. Seetõttu loodi lahendus, mis võimaldas rallidroonide signaali suunda detektori suhtes leida kasutades motoriseeritud suundantenni ja tarkvaralist raadiot. Seadme testimisel leiti, et juhul kui droon oli kaugustel 25m kuni 250m, oli keskmine viga rallidrooni suuna leidmisel detektorist relatiivselt väike.

Võtmesõnad: Rallidroon, tarkvaraline raadio, suuna määramine, raadiolokatsioon, HackRF One

CERCS: P175 Informaatika, süsteemiteooria

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Introduction

The proliferation of fast flying first-person view drones as weapons of war [15] has shown the need for systems which could detect and warn about the presence of such drones. Due to the large number, affordability and small physical size of these drones, they can pose various risks, such as physical harm and privacy violations [26]. As such, an increasing number of institutions require information about where such drones are in relation to their own location. Although there are existing detection systems, they are often not economically viable or not readily available. Thus an affordable system for direction-finding such drones is needed.

The aim of this thesis is to test the feasibility of a low-cost solution which would allow for the direction finding of first-person view drones by their radio emissions. A low-cost solution is proposed and designed, which uses readily accessible electronic components. The focus is placed on the accuracy of direction finding, the direction at which a drone is relative to the position of the detector. The detected distance from the device to a drone or the time it takes for acquiring the direction are out of scope for the thesis. The proposed system's accuracy is evaluated with real-world testing using first-person view drone hardware.

In the first section, first-person view drones and their characteristics are covered, with focus put on their radio emissions - the types of radio signals, signal characteristics and how they are transmitted. The second section covers common methods of radio signal direction finding, as well as devices which allow for reception and analysis of radio signals. Methodology is covered in the third section of the thesis, where the choice of hardware and software solutions are explained. The results and the process of testing the low-cost solution is covered in the fourth section. The results and future work are discussed in section five.

1 First-person View Drone

In this section, the anatomy of first-person view (FPV) drones will be explained as this knowledge is necessary to understand how these types of drones can be located. FPV drones are characterised by a low-latency video transmission between the drone and its operator [10]. While other drones typically experience over hundreds of milliseconds of latency when transmitting live video to the operator, FPV drones are designed to transmit video at a low latency between 17ms and 40ms, which is the time it takes for an image to be recorded and sent by the drone and received and displayed to the operator [10]. This fast video transmission enables pilots to react quickly to changes and makes it possible for the operator to fly the drone manually, generally without requiring any flight assist or flight stabilisation systems which are common on other drones.

1.1 FPV Drone Video Transmission System

The video transmission system of an FPV drone consists of a camera, a video transmission module (VTx) and an antenna. The video transmission module transmits the video signal it receives from the camera to the operator using the antenna. This video signal is then received and viewed by the operator to fly the drone. Analog video cameras and VTx boards are used on FPV drones due to the low latency, small size and low cost when compared to digital alternatives [10].

The two types of analog encoded video signals mainly used by FPV drones are Phase Alternating Line (PAL) and National Television System Committee (NTSC). The choice of encoding is dictated by the type of the video signal outputted by the camera on the FPV drone. Many cameras can be manually switched to output either of the two, while some are hard-coded to output only one type of signal. Resolution of the video signal with these encodings is at best around 720p, with the frame rate at 30 frames per second [23]. The frequencies at which these analog signals are transmitted by the VTx are divided

into bands, which each have 8 channels. The main five bands are A, B, E, F and R, with five more in lesser use around the world [13]. Bands A, B and F are in their entirety in the 5.8 GHz ISM band [10].

1.2 Characteristics of the Antennae Used on FPV Drones

Different types of antennae can be used to transmit a video signal to the operator which can have different parameters. An antenna can be classified as either directional or omnidirectional. Omnidirectional means the orientation of the antenna is not important as it can transmit and receive signals in a 360 degree horizontal pattern around it [16]. Directional antennae are better suited for communicating in one direction. FPV drones mostly use omnidirectional antennae to transmit video signals because of the uncertainty of the drone's angle towards the operator's receiving antenna.

The antennae can additionally be categorised by their polarization. When talking about polarization, the main focus is on the electric field of an electromagnetic wave generated by an antenna. Here, polarization is referred to as the direction at which a wave oscillates relative to the direction where the wave travels [20]. A signal is linear polarized when the electric field of the signal, if viewed from the perspective of the transmitter, is oscillating in a linear pattern - up and down is called vertical polarization, left and right is called horizontal polarization [21]. When transmitting and receiving using linearly polarized antennae, the best signal strength is achieved when both antennae are oriented such that they are polarized along the same axis, for example two hand-held radios have the best signal reception when both have their vertically polarized linear antennae as upright as possible.

For circular polarization, the signal consists of two equal magnitude orthogonal waves that are 90 degrees out of phase. These two waves combine to create a circular signal that has an electrical field which rotates as the signal propagates. If the rotation vector is

viewed from the perspective of the transmitter, the signal rotates to the right and is called right-hand circular polarization (RHCP), but if it rotates to the left, it is called left-hand circular polarization (LHCP) [21]. The abbreviations RHCP and LHCP are widely used when circularly polarized antennae are discussed. To summarise, if FPV drone video signals are to be received and analyzed, an antenna with matching characteristics to the FPV drone's transmission antenna must be chosen. Not matching the characteristics might reduce or make it impossible for the signals to be acquired.

1.3 Types of FPV Drone Video Transmission Antennae

While the linear antennae designs are often straightforward, circularly polarized antennae have more complex designs. There are two circularly polarized omnidirectional antennae designs used on FPV drones called the cloverleaf antenna and the pagoda antenna. Both antenna designs are used extensively when Super high frequency (SHF) video signals are transmitted from FPV drones, with the pagoda being a new open-source antenna designed to be made from printed circuit boards (PCB) to reduce manufacturing complexity and to have a good omnidirectional radiation pattern [2]. The pagoda design is also more durable than the cloverleaf as the cloverleaf can more easily bend out of shape under physical forces. The cloverleaf design is also widely used due to it having good transmission characteristics [14].

For receiving circularly polarized signals, the most common antenna types are helical and patch antennae. The helical antenna consists of a ground plane and a protruding spring-shaped wire. The amount of full turns of the spring-shaped wire on the helical antenna dictates its gain - an antenna with more turns is longer and has higher gain [12]. Patch antennae are directional antennae mounted on printed circuit boards, and can be polarized both linearly or circularly. They are compact and more cost-effective compared to the helical antennae. They have lower efficiency due to using circuit boards as dielectric

material instead of the air which fills the gaps between the twisted wire of a helical antenna [14].

1.4 Frequencies Used for Operating FPV Drones

Industrial, Scientific, Medical (ISM) bands are frequency ranges which have been designated by the International Telecommunication Union (ITU) as frequency ranges for use by the general population [18]. Almost all consumer electronics with radio frequency (RF) emissions use these frequency bands. Ultra high frequency (UHF) ranges from 300 MHz to 3000 MHz and is used to send control signals to an FPV drone or to receive video back from it [13]. In the UHF range, the most common ISM band used for communications with drones [13] is the 2400 MHz - 2500 MHz ISM band [8]. Additionally, ranges around frequencies 433 MHz, 800 MHz, 900 MHz and 1200 MHz are used depending on the region of the world [13]. The 800 MHz, 900 MHz and 1200 MHz frequencies are not designated as worldwide ISM bands by the ITU, while the 433 MHz band is an ISM band in the region where Estonia belongs [8]. Super high frequency ranges from 3 GHz to 30 GHz and are mainly used for video signals transmitted from FPV drones.

The worldwide ISM band from 5.725 GHz to 5.875 GHz [8] is mainly used for the purpose of video transmission in FPV drones, as the 150 MHz bandwidth of the aforementioned ISM band can accommodate a number of simultaneous FPV video signals without the signals interfering with each other [13]. This knowledge is necessary to select a direction finding method and a device for capturing and analysing FPV drone video signals, because the chosen device must be able to receive signals in the 5.725 GHz to 5.875 GHz frequency range. In the next section, direction finding methods and devices for processing signals will be discussed.

2 Direction Finding FPV Drone Video Signals

Direction finding of RF signals is a challenge that has existed since the development of the first radio emitters. Finding the direction of radio signals emitted by FPV drones can be characterised by the fact that FPV drones as emitters can either be stationary or moving at high speeds, thus complicating some RF direction finding methods or increasing the error in the measured direction for some methods. As such it is necessary to understand what common RF direction finding methods can be used to measure the angle from which an RF signal is reaching the position of a measuring device. The high frequency ranges used by the FPV drones additionally complicate the use of some direction finding methods, because the method must be able to be constructed such that it would work in the 5.725 GHz to 5.875 GHz ISM band for it to be able to receive FPV drone video signals which are in that frequency range. The following paragraphs will discuss different methods for finding the direction of an incoming RF signal.

2.1 Watson-Watt Method

The Watson-Watt radio direction finding method is a method which utilizes a minimum of 4, ideally 5, antennae in an array to determine the direction of an arriving signal by measuring and comparing the received signal from each antenna in its array. The array itself is called an Adcock array - four antennae are arranged in a cross pattern, with an additional fifth omnidirectional antenna in the center of the setup. The method calculates the angle of arrival of a radio signal by comparing the amplitude differences between signals received at the different antenna elements. Specifically, it produces outputs by subtracting the signals from pairs of antennae along the North-South and East-West axes, and comparing these to the omnidirectional signal from the center antenna [6].

The method covers the horizontal axis, but requires more complicated receiving hardware, as all five antennae must be connected to a receiver so that their signals could be compared.

Additionally, a built Adcock array will only work for a very narrow frequency range [6].

2.2 Pseudo-Doppler Method

The following paragraph uses [19] as reference. The Pseudo-Doppler method is a signal direction finding method with no moving parts. Receiving omni-directional antennae are arranged in a circle with constant spacing. As a signal reaches the array, each antennae is sampled sequentially by the system in a circle to simulate an antenna which is rotating at a fixed speed. This simulated movement changes the frequency of the received signal due to the Doppler effect - the frequency of the received signal increases if the current sampled antenna is towards the signal source, and the frequency of the received signal decreases as the antennae which is sampled is further from the source direction. Thus, at each antennae the received signal is frequency modulated and using the known speed at which antennae are sequentially sampled, the incoming direction of the signal can be determined.

One weakness of the system is that in order for the direction to be established, the signal must be received during the duration of a full circular sample [4]. Thus it can be understood that signals which are shorter than the time it takes to sample all antennae can either be missed or have their direction misinterpreted. For analog FPV video signals, this is not the case, as the FPV drones emit a constant signal. Because of the requirement of a fast switching circuitry to switch between receiving antennae, this system was not used in this thesis, as the difficulty of acquiring one would not have been a low-cost solution, but the method shows good promise in further developments for direction finding of FPV drone video signals.

2.3 Correlative Interferometry Method

Correlative interferometry is a radio direction finding method used to determine the direction of a signal by analysing the differences in the phases of the signal received at multiple antennae in an array. As an RF signal arrives at an angle to the antenna array, it travels different path lengths to reach each antenna, creating phase differences that depend on the distance between antennae and the signal's wavelength. By comparing these phase differences across all pairs of antennae, and matching them with known patterns, the system can accurately pinpoint the signal's direction. Correlative interferometry offers high angular resolution but requires a complex and expensive setup because it relies on a large number of antennae to be set up in an array [4].

A complex receiver device is required that has inputs or channels for each antennae, and manufacturing of the array has to be precise if it was to be used to perform direction finding either on the 2.4 GHz or on the 5.8 GHz ISM bands. Due to the complexity of manufacturing such an antenna array at the required accuracy and the complexity of combining it with a suitable radio signal receiver, correlative interferometry was not considered as a low-cost solution for locating FPV drones in this thesis. The complexity and thus the cost of the array are out of scope for the thesis.

2.4 Direction Finding with a Directional Antenna

One way to find the direction of a signal is to use a directional antenna and a receiver which outputs the received signal's strength to the user. The antenna is manually rotated around a single point until the strongest arriving direction of the signal is determined. While a simple method, the accuracy of the measured direction is heavily affected by the operator [3]. An automatic system would negate the user error, thus improving direction finding accuracy, but increasing the complexity and the likely monetary cost of such system.

When an accurate direction of arrival is required and the method of using a directional antenna is utilised, such improvements should be considered. Additionally, the receiving device must be capable of reception in the frequency ranges at which the source of the signal can be found. Since this method has the most promise in being a low cost solution and it has the simplest physical construction complexity, the method is chosen in the thesis for signal direction finding. In the following chapters, devices are explored which would enable the use of this direction finding method.

2.5 Software-defined Radio Devices

A software-defined radio (SDR) is a device capable of transmitting and/or receiving radio signals. While some components of the device are implemented in hardware, some are implemented in software [1]. SDR devices have some parameters set by their physical implementation, such as the lowest and highest frequency a device can transmit or receive on, the minimum and maximum width of the frequency band at which it can receive/transmit, or the maximum and minimum rate at which it can sample signals. Within these ranges however, parameters such as the center frequency at which the device is tuned to or the bandwidth measured by the device can be rapidly adjusted in the device's firmware [9]. This enables an SDR device to be extremely flexible and have use in numerous applications. Typically the higher the supported frequencies, the higher the price of the device. The mentioned capabilities of SDR devices enable an SDR device to be extremely flexible and have use in numerous applications, hence why SDR was selected as a tool for use in this thesis.

2.6 Direction Finding Devices Capable of SHF Signal Reception

Because FPV drones mostly broadcast their video on the 5.8 GHz ISM band, a device which supports SHF signals is needed. Currently not many SDR platforms exist which are

capable of processing signals at 5.8 GHz ISM frequency bands, and the devices which do support it, have a high unit cost, thus not being an affordable option for direction finding FPV drone video signals. In this section, multiple SDR devices and their attributes are explored.

2.6.1 KrakenSDR

One example of a direction finding device which works in the 24 MHz to 1766 MHz range is the KrakenSDR. This SDR supports five simultaneous antennae. The device combines five smaller receivers built into one SDR package and keeps them synchronized and coherent using a single oscillator, thus enabling direction finding using the correlative interferometry technique. The device comes with accompanying direction finding software, which makes it ideal for direction finding signals in the device's stated 24 MHz to 1766 MHz tuning range [11]. The device leverages cheap mass-produced components to decrease its price to a reasonable level. At the time of writing, the device can be bought for 464.07€ (including VAT)¹, with an optional five antennae for 185.08€ (including VAT)².

Due to the ease of use and price of the system, it would be a good choice for direction finding FPV drones video signals if the drone was to broadcast its video feed in the KrakenSDR's supported frequency range. However, because the most common 5.8 GHz ISM band used by FPV drones is not supported by the device, it can not directly be compared to other FPV drone video signal direction finding devices as it is not capable of SHF signal reception.

¹<https://www.mouser.ee/ProductDetail/KrakenRF/KRAKENSDR-01?qs=A6e0%252BMLsxmSq%2FAeS4o1tRw%3D%3D>

²<https://www.mouser.ee/ProductDetail/KrakenRF/KRAKENANT-01?qs=A6e0%252BMLsxmRG8NAZSC0IfA%3D%3D>

2.6.2 SignalHound BB60C

The SignalHound BB60C is an SDR device which supports receiving signals in the frequency range of 9 kHz to 6 GHz, with a maximum supported bandwidth of 27 MHz [22]. The lowest price of one unit is listed as 3,489.12€ (including VAT)³. The device comes with signal spectrum analyzing software, but not with direction finding software [22]. As such, custom direction finding software would have to be written to enable direction finding. The relatively high price of one unit makes it an uneconomical option for analysing FPV drone analog video signals.

2.6.3 USRP B200mini

The cheapest 5.8 GHz ISM band capable device from Ettus Research, this SDR device called USRP B200mini has a cost of 1,258.44€ (including VAT) at the time of writing. The device does not come with direction finding software. It has a frequency range of 70 MHz to 6 GHz, and maximum bandwidth of 56 MHz⁴. The ability to receive at a frequency up to 6 GHz means the device is able to process FPV drone video signals. Due to the relatively high price of the unit, it was not considered as a cost-effective option for the thesis.

2.6.4 HackRF One

HackRF One is an SDR platform capable of SHF signal reception and transmission and is thus able to receive FPV drone video signals. Specifically, it has a frequency range of 1 MHz to 6 GHz where it can both receive and transmit. The device has an adjustable sampling rate between 2 MHz to 20 MHz⁵. The safe maximum receive power of the device is -5 dBm, with 10 dBm being a recommended upper limit⁶. Receiving signals

³<https://signalhound.com/products/bb60c/>

⁴<https://www.ettus.com/all-products/usrp-b200mini/>

⁵https://hackrf.readthedocs.io/en/latest/hackrf_one.html

⁶<https://hackrf.readthedocs.io/en/latest/faq.html#what-is-the-receive-power-of-hackrf>

with higher power output might damage the device.

On the HackRF, measured signal strength can be increased by turning on an amplifier with 11dB of gain, or by adjusting the Low Noise Amplifier (LNA) gain from 0dB to 40dB in 8dB steps and the Variable Gain Amplifier (VGA) which can be adjusted from 0 dB to 62 dB in 2dB steps⁷. These gain settings, based on experimenting with the device, are settings which change the received/transmitted signal's characteristics - LNA gain helps to bring out weak signals, while VGA gain increases signal strength of the whole bandwidth of signals processed by the SDR.

Due to the high frequency range available, the device is suitable for the measurement of FPV drone signal emissions. Additionally, the cost of one unit is the lowest observed at between 299.00€ (including VAT) [5] to 321.90€ (including VAT)⁸ from different retailers and as such, it is the lowest cost option for analysing 5.8 GHz ISM band signals. The creator of the device, Great Scott Gadgets, does not sell the device directly, but through other resellers, and as such the price of the unit varies⁹. Being the cheapest option for processing 5.8 GHz ISM band FPV drone video signals, the device was chosen as the SDR platform for signal reception and processing in the thesis.

Zhang et al [27] has demonstrated that the HackRF One can be used for direction finding of signals using the correlative interferometry method mentioned earlier in this thesis. In their setup, an array of four antennae required five HackRF's, one HackRF for each of the four antennae and one HackRF to synchronize the receiving HackRF's such that the incoming signals could be compared. The use of five devices means the setup was not low-cost. Thus in this thesis, a solution with only one HackRF is explored, utilising the direction finding method of using a directional antenna for strongest signal direction determination. Because no mention of such solution which uses a HackRF and an

⁷<https://hackrf.readthedocs.io/en/latest/faq.html>

⁸<https://www.wimo.com/de/hackrf-one>

⁹<https://greatscottgadgets.com/wheretobuy/>

automatic directional antenna could be found in literature, and as such the solution can be considered as a unique contribution. In the next chapter, this method will be explored.

3 Methodology

In this section, the methodology used to find the direction of a FPV drone's video signal in a cost-effective way is outlined. An array of multiple antennae with an accompanying antenna switch would have a high complexity and cost. Thus a simpler signal direction finding system was devised which would consist of an automatically moving single directional antenna connected to an SDR platform. The system would be able to perform measurements in a radius around the device and at any elevation above the horizon. Thus a mechanically operated directional antenna system was decided upon. Accompanying software was designed which could visualise the direction of the strongest measured FPV drone video signal.

3.1 Choice of Hardware

To achieve a mechanically steered system which would support a directional antenna, a design with two servos was chosen which would allow for the system to have full 360 degree movement range - one servo for horizontal, and one for vertical movement. Waveshare ST3215 servos were selected for this purpose.

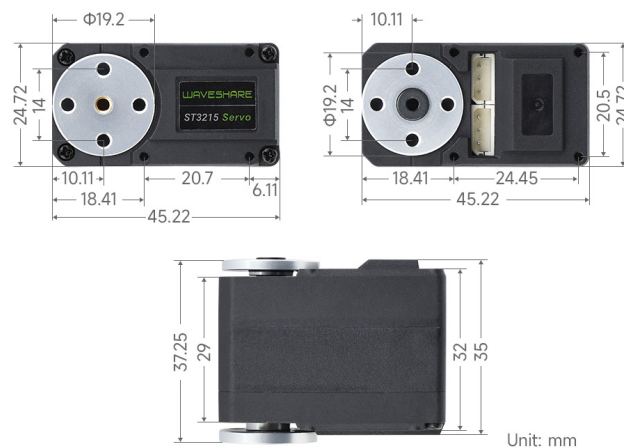


Figure 1. The servo model ST3215, used for direction finding [24].

Figure 1 shows the model of the servo which was used in the direction finding device's construction. The cost of a single servo was 20.10€ (including VAT) [24]. The chosen servos support 4096 separate positions and have a magnetic encoder which measures exactly the position of the servo [24]. This allows for the system to know at all times the position of the servos and thus the direction at which the antenna is pointed at. The servos are controlled by a servo controller board which has an ESP32 microprocessor.

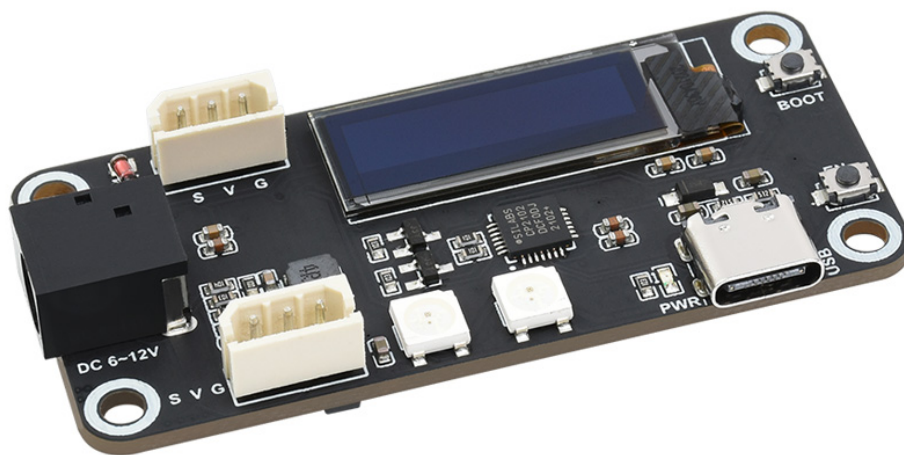


Figure 2. The servo driver board with an ESP32 microcontroller [25].

Figure 2 shows the chosen servo controller board. Cost of one board was 14.61€ (including VAT) [25]. On the image, a power connector can be seen on the left side of the board. Here a 12V power supply was connected to power the board and the servos. USB type-C female connector can be seen on the bottom right of the board, through which the controlling computer was connected to, on which the GUI and the signal processing was ran on. This servo board was chosen because it had easy software implementation and was designed by the manufacturer to control the chosen servos[25]. Two white Universal

asynchronous receiver-transmitter (UART) interface connectors can be observed on the left side of the board, with the top one being used to connect to the horizontal movement servo. From Figure 1 it can be seen that each servo has two UART connections. The Vertical servo was connected to the horizontal servo using an UART cable.

Communication to the vertical movement servo was done through the horizontal movement servo. Furthermore, software was written which enabled rapid communication over USB serial connection between a computer and the ESP32 servo controller board. The mechanical steering system makes it possible to perform measurements in any direction, thus enabling direction finding, although at the cost of traverse time between measuring points being slower than a system without no moving parts. This however was deemed enough to test the feasibility of low-cost FPV drone video signal direction finding as it accomplishes the task of finding the direction of a FPV drone video signal.



Figure 3. The helical antenna used for direction finding [17].

For the antenna, a right-hand circularly polarized helical antenna was chosen due to its low cost, high directivity and high gain to increase the chances of detecting a signal at

longer ranges. Circular polarization was chosen to reduce error caused by multipathing or reflection issues. Figure 3 shows the antenna used in the construction of the drone detector [17]. A short coaxial cable protrudes from the antenna and is used to connect to the desired receiver. From Figure 3 it can be seen that the antenna is constructed of 3D printed material and a copper wire. The cost of one unit was 29.90€ (excluding VAT) [17]. This was deemed as a low-cost antenna solution. The antenna had the following parameters as described by the manufacturer:

- bandwidth of 5640 MHz - 5945 MHz;
- beam width of 30 degrees with highest gain;
- gain of 14 dBi;
- 12 turns.

The SDR platform chosen for signal measurement was the HackRF One. The device has great software compatibility and has the technical capabilities to measure analog video signals sent out by FPV drones. Additionally, as HackRF One devices were in the inventory of the Institute of Computer Science and readily accessible in numbers. For these reasons, the device was chosen for the experiment. The HackRF One, which was used for the drone direction finder, had firmware version 2023.01.1 (API:1.07) and hardware revision r7.

The total cost, including VAT, of the two servos, the directional antenna and the servo controller board was 91.59€. The HackRF was loaned from the Institute of Computer Science for the duration of testing. The lowest price mentioned earlier in section 2.6.4 for a HackRF One was at the time of testing, 299.00€, and as such the total cost of the main components of the device total to 390.59€, which is lower than existing feature complete devices built for SHF signal direction finding, such as the Bird SH-60S-AOA¹⁰.

¹⁰<https://btgstore.com/shspan1.html>

As such, the drone detector designed in this thesis can be considered a low-cost solution.

3.2 3D Printing

To mount the servos, HackRF One SDR device, directional antenna and the servo controller board, 3D printing was used to manufacture the parts that would allow simple integration of these listed functional components. In addition, a mounting hole for a ¼ inch common tripod attachment screw was integrated, such that the system could be mounted on a tripod. This is a common screw size used on camera tripods and equipment, thus enabling compatibility with common tripod equipment. The opted design of the components serves only to provide a rigid and stable platform for the scanning antenna system and as protection to the servo controller board from unexpected physical contact.

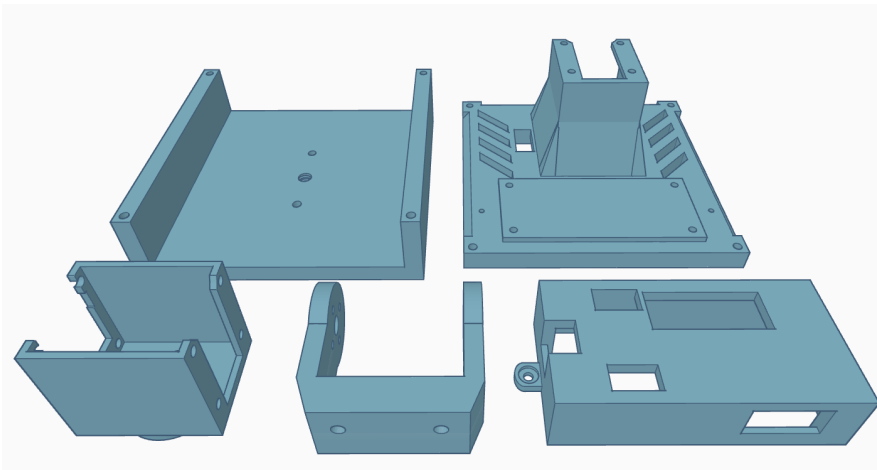


Figure 4. View of all the designed 3D models.

Figure 4 shows five 3D models which make up the shell of the device. On the top row, the bottom and top plates are seen which encapsulate the HackRF device. The top plate has a position for one servo which actuates the receiving antenna horizontally. Additionally, the top plate has mounting points for the servo controller board. On the bottom row of Figure 4, the bottom left model depicts the housing of the servo which rotates the antenna

vertically. In the middle, a mount between the vertical movement servo and the antenna is shown. Lastly, bottom right model shows the design of a housing which was printed to provide protection for the servo controller board from accidental physical damage.

Models of all of the separate parts were designed in 3D modeling software Autodesk Tinkercad¹¹. Tinkercad was used as it provided sufficient complexity for designing the parts, while being free to use and relatively simple to get started with. The models were printed with a Weedo3d TINA2 fused deposition modelling printer¹². The material used to manufacture the parts was polylactic acid (PLA). PLA was chosen as it was readily available within the faculty.

3.3 Software

The software which handles requests and sends back telemetry and servo position to the computer was written in C++ programming language. It uses a serial connection over USB to communicate between the host computer and the ESP32 microcontroller servo controller board itself. The code starts automatically as the servo controller board is powered on, transmitting servo telemetry to the main computer.

The Graphical User Interface (GUI) and its underlying signal processing was written in Python. Python was chosen as it had preexisting libraries for communicating with the HackRF SDR device and for processing the signals which it receives. The back-end code can be viewed in the GitHub repository of this thesis (Appendix III). The GUI was written with an immediate-mode GUI toolkit in Python called DearPyGUI¹³. This toolkit was chosen as it allows for fast rendering of graphs and basic graphics for showing the direction of signals, and is simple to work with.

¹¹<https://www.tinkercad.com>

¹²<https://www.weedo3d.com/fr-fr>

¹³<https://dearpygui.readthedocs.io/en/latest/index.html>

3.4 Signal Processing

For this thesis, it was assumed that only one FPV analog video transmitter is being observed, and that the device is stationary. It is further assumed that the direction with the strongest signal strength is the direction of the FPV drone. To be able to determine the direction with the strongest signal, the received signal strength was calculated in many points around the device. To achieve this, at each position, the HackRF One was used to capture a 20 MHz bandwidth of data next to the frequency of signal of interest such that the signal fully fell within the captured 20 MHz bandwidth. During testing the bandwidth was centered in this way because scanning a larger range of frequencies would not have aided in understanding the accuracy of the system and thus was considered outside of the scope of this thesis.



Figure 5. Image of a received drone video signal.

The Power Spectral Density (PSD) method from Matplotlib¹⁴ was used to compute the received signal's strength. The PSD method creates an array of data where for each frequency that was captured, the strength of the signal in milliwatts at that frequency is calculated. If a signal with a strength significantly above the noise floor was discovered, it was considered an FPV drone signal. Figure 5 shows a signal on the right side of the

¹⁴https://matplotlib.org/stable/api/_as_gen/matplotlib.pyplot.psd.html

image emerging from the noise. The jagged line on the bottom of the image is the noise floor, also called the background noise. The bottom numbers are frequency in MHz. The orange line depicts a dynamically calculated level of desired signal strength. This line was used to ignore weaker signals - if a signal was below it, it was considered noise. The method for calculating the line can be found in the GitHub repository of the thesis (Appendix III). This calculation was determined experimentally and was found to be sufficient at filtering out unwanted weak signals.

No signal identification was performed, because a section of the radio frequency spectrum was chosen such that no other interfering signals could exist which would be strong enough and thus would be mis-identified as a signal from an FPV drone. If the signal's strongest point's frequency fell within an FPV video transmission channel, it was assumed it is a drone transmitting on that channel.

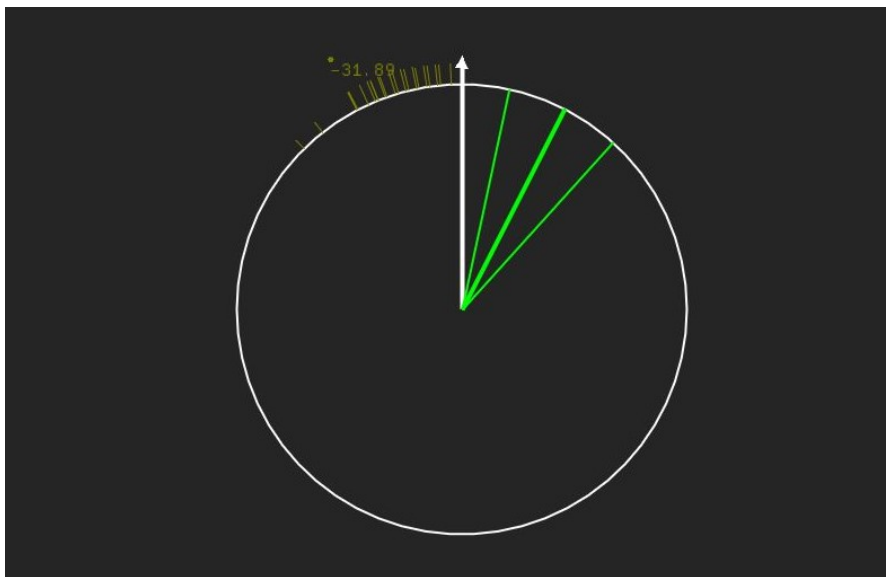


Figure 6. Compass element displaying a signal on the GUI.

Figure 6 displays the GUI program's compass view which is updated to show the signal of the designated channel. The found signal is displayed as yellow lines - each line and

its length representing the strength of the signal in that direction. The longer the line, the stronger the signal in that direction. The strongest direction of the signal is marked by a dot and its strength in decibel-milliwatts. Each time a stronger signal is found, the position of that source is used to show the new strongest signal direction in the GUI. The thick green line represents the current direction of the antenna, with the small side green lines creating a 30 degree cone around the antenna's direction - the angle at which the directional antenna has its highest gain. The white line depicts the forward direction - the direction at which the scanner starts and which it considers forward.

The scanning method used to achieve this information which is displayed on the compass view in 6 would be set in the GUI software. The user can set the number of positions to be scanned, either over the whole horizontal plane around the scanner, or over a desired section in a chosen direction. The density of scans could thus be varied depending on how high of a scan resolution the user requests.

4 Testing and Results



Figure 7. Close-up view of the drone detector.

Figure 7 shows a close-up view of the drone detector without any attached cables to the HackRF or the servo controller board. The antenna is pointed forward. This was the device used for performing measurements on the field. It was placed on a tripod. A bubble level was used to verify that the drone detector is level. When performing measurements, the servos were instructed to move to a position, a scan was performed and the servo positions were measured. This was repeated until the desired angle was covered in the desired amount of scans. Results of these sweeps with multiple scans were shown on the GUI program, which will be showcased in the following section.

4.1 Overview of the Direction-finding GUI Application

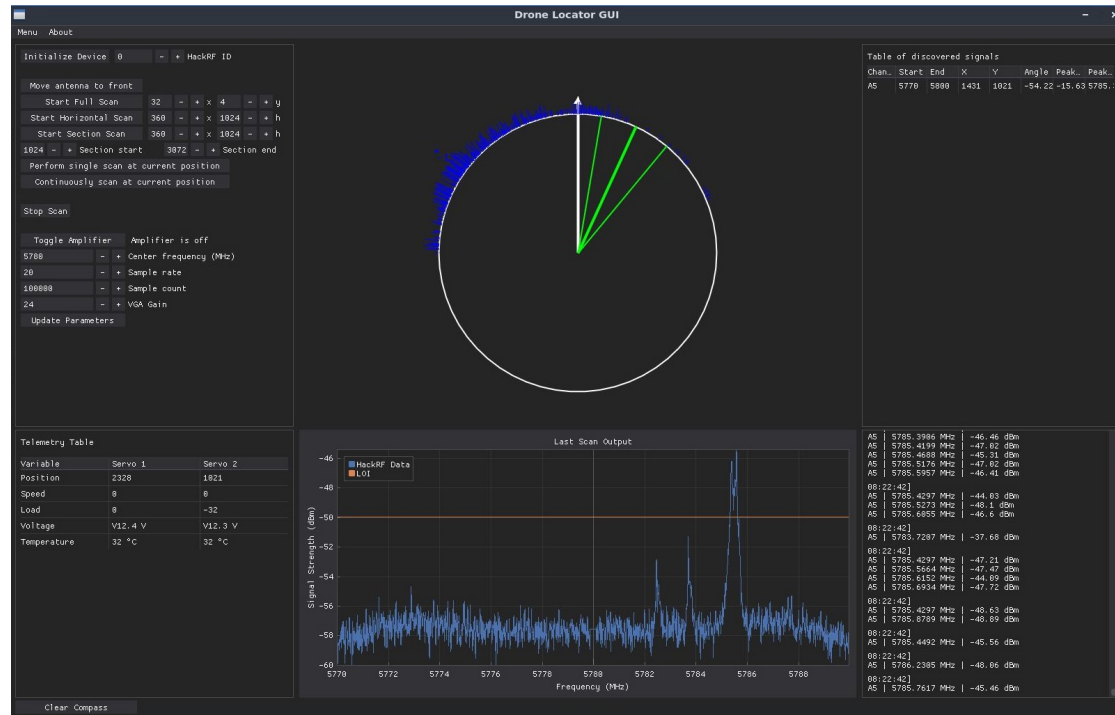


Figure 8. GUI program with signal from a drone simulator.

Figure 8 shows a complete overview of the GUI program which is used to find the direction of the FPV drone video signal. The screen is divided into six areas of interest: on the top left, the panel has multiple controls for different measuring modes and options to change parameters for how measurements are to be taken. For example, the user can scan a horizontal section at a desired height with a chosen amount of measurements done along that section, or continuously scan at a position the antenna is currently pointed. Additionally, the user can change the scanning parameters to fine-tune the scanning of signals.

Bottom left of the Figure 8 shows the position and other telemetry of the servos in real time. Top middle is the overview of received signals - in blue, a signal is detected, with that signal's historical strongest direction being to the left of the forward position of

the drone detector, indicated by the little blue dot over one of the blue lines which is drawn on the circle. Below the direction view, in the bottom middle, is a frequency graph showing the last measured bandwidth - on the x axis are frequencies, while on the y axis, signal strength at each frequency is shown. The orange interest level line can also be seen there, which denotes that signals below it are considered noise.

The top right of Figure 8 shows a table of discovered signals. For each discovered signal, the channel at which it fits into is shown, along with that channel's expected bandwidth's start and end frequencies. The servo position, noted by the x and y columns, where the most strongest signal has been found, is also shown. Adjacent to those, the angle to the left or to the right of the center line is shown in degrees between the center line and the strongest recorded signal's direction. The value is between -180 degrees and 0 degrees, or 180 degrees and 0 degrees, depending on if it is to the left or to the right of the center line, respectively.

At the bottom right of the GUI is a log which shows all measurements which are compared to the current strongest found signal for that channel. If a signal which had stronger signal strength was discovered, it would be set as the new strongest signal. The compass view in the top middle of Figure 8 would also be updated accordingly, along with the table view to the right of it.

4.2 Method for Measuring Direction-finding Error

Due to lack of reliable method of zeroing the drone detector on a target for measuring the error at which the scanner would find the drone, a method was devised which enables the measurement of error without precise alignment between the drone detector and a transmitter. The method consists of three points, each of which has its location precisely known. For example, points A, B and C are chosen. If the co-ordinates of the points are known, the angle ABC can be calculated. This angle can be then compared to an angle

measured by the drone detector if it is at point B with its forward direction anywhere towards the two other points, while transmitters are placed at points A and C. The difference between the calculated angle and the measured angle can thus be taken as error at which the device can measure the direction of two points.

While the described method does not yield a direct single signal source measurement error, it allows for reasonable understanding of the device's capabilities. With this method, the measured error can be viewed as a worst-case error. For example, if the direction of one signal is measured correctly but the other signal's direction with some error, we can conclude that for either of the two points the error at which their direction was measured could not have been greater than the error at which the angle between the two points was measured.

To enable this method, an accurate system of measuring positions in the real world was required. A correction service augmented¹⁵ GNSS receiver SOUTH GALAXY G2¹⁶ with guaranteed 2cm accuracy was used for the measurement of the in-world points. Each position was measured twice, separated by one hour to reduce the chance of any interference altering the measurements. The average of the two measurements was then written down as the location. Each position was marked exactly with a stake which was pushed into the ground, over which the drone detector or the drone simulator were positioned.

¹⁵<https://geospatial.trimble.com/en/products/correction-services/trimble-vrs-now>

¹⁶<https://southinstrument.com/uploads/file/2023-05-09/645a0e5e5fb8f.pdf>



Figure 9. Overview of selected points for error measurement.

Six distances were chosen for testing: 25m, 50m, 100m, 150m, 200m and 250m. The co-ordinates of the twelve transmission points and the one drone detector point were measured as described, and the angles between the pairs of points at each distance were calculated. These angles between two points at each distance were computed based on the measured coordinates. These computed angles were compared to the measured angles to get the error at which each distance the drone detector is able to measure signal direction. In Figure 9, the total 13 positions can be seen, with the angles in degrees between each point pair at different distances can be found. The drone detector is positioned on the bottom right tip position. The points are at the ends of each distance line, but due to how in-line all of the points are and how little the points deviate, Figure 9 should be taken as an overview of the test site. Additionally, the distance to each left point is shown in meters. The distances to the points on the right were similar.

The site at which measurements were taken was a grass field (Appendix II). The left points had 15cm of grass from the ground, while the right points had nearly 120cm of

tall grass. The testing site was far away from any other signal sources and it was verified by observation of the radio spectrum that no interfering signals near the used frequencies existed, and that the only signal would be the drone simulator's signal. Additionally, the transmit power of the drone simulator was varied - at longer distances, the transmit power was increased. This enabled better signal reception and made sure the error measurement would not be affected by the inability for the drone detector to see the signal - the received signal was kept strong enough for the drone detector to always be able to find the signal.

4.2.1 Drone Simulation and Signal Generation

Common commercial FPV drone components (Appendix I) were used to generate signals for testing of the direction finding system. A camera, video transmission board and an antenna were used to generate testing signals. The camera generated a PAL encoded signal which is transmitted by the transmission board. PAL was chosen because it was the default mode on the camera. The transmitter is able to transmit at five different channels of A, B, E, F and R, which each has 8 sub-channels. To simplify testing, only the A5 sub-channel was utilised. The A5 channel was chosen as it has its center frequency in the center of the best reception range of the drone detector's directional receiving antenna which is between 5760 MHz and 5810 MHz. For transmission from the drone simulator, a pagoda antenna was used to transmit the video signal. The antenna was right-hand circularly polarized, had a gain of 1.1 decibel-milliwatts and had an ideal operating frequency between 5730 MHz to 5829 MHz.

The FPV drone simulator was powered using a battery pack for mobility and ease of testing. Additionally, a cooling fan was mounted to cool the video transmitter, because during testing it was observed that the video transmission board's temperature rises rapidly as the device operates. To avoid damage to the board from overheating, a 12V DC fan, which is also powered from the same battery pack, was installed to blow air over the video transmission board to reduce its temperature as it operates. This kept the video

transmission board operating at reasonable temperatures.

4.2.2 Automated Testing

To simplify and enable accurate testing of the drone detector, a testing script was created. The script uses the same back-end as the GUI program, but does not show any GUI elements - instead, measurements are saved in comma-separated value (CSV) text file format. The script hard-codes certain parameters - the drone detector has its center frequency set such that it would always be able to measure the signal from the drone simulator, and the HackRF device of the drone detector has its LNA gain and VGA gain both set to 24. The script was run to test error at different distances. As the testing script is started, it first creates the CSV files into which it writes logs, and then waits for input until the drone simulator is placed on the left position. It measures the direction of the drone signal 10 times and takes the average of the 10 measurements, then waits for user confirmation until the drone simulator is placed on the second adjacent right position, where it also performs 10 independent signal direction measurements and computes the average direction angle. All measurements are saved in the generated log files, where for each measurement, the best found direction and signal strength are logged. An angle is then calculated between the two average measured angle directions. The script shows the results to the user, after which it has completed execution and can be executed again at new points and a new distance.

For testing, four scans per degree were performed over a 22.5 degree angle towards both left and right points from the center line. The 22.5 degree angles, 45 degrees in total, was determined experimentally to be an angle wide enough for testing purposes, while remaining small enough for the scanner to not take too much time to perform the scans.

4.3 Results

Figure 10 depicts an overview of the measurements taken for error analysis. It shows the measurement of the drone simulator's video signal direction at 6 distances. At each distance, the drone simulator was placed at two positions which were both measured 10 times in a way that each measurement was unaffected by previous measurements. The green colored measurements were done over the area of the field where short grass grew, while the blue measurements were done over tall grass. The dots depict separate direction finding results for both the left and the right position - the directions at which the strongest signal were found to be coming from towards the drone detector. The crosses are an average position calculated for each test from the 10 measured directions. The center line on Figure 10 depicts where the drone detector was facing - the direction at which the detector was physically set up and which it considers direct forward heading. The angles between the center line and the average of measurements are also displayed on the graph.

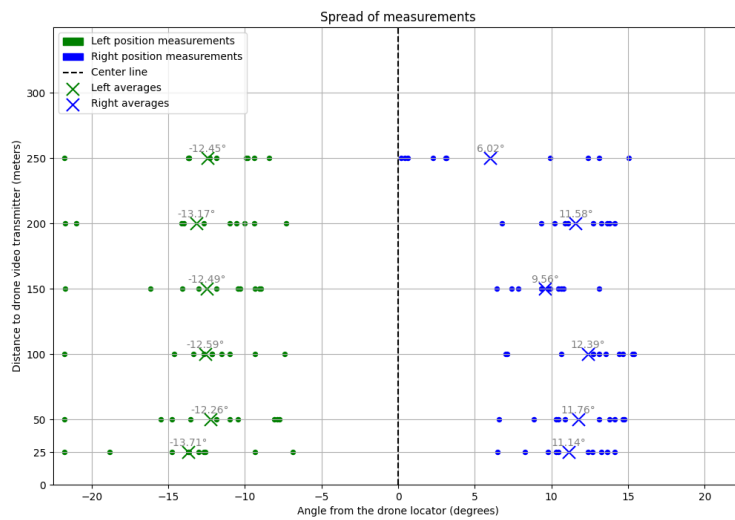


Figure 10. Overview of measurements of pairs of positions at six distances.

Overall, it can be observed that for the majority of the measurements, the found incoming signal directions seem to be spread over a 10 degree angle. Two outliers can be observed however - at 25m, the left position has its measured directions be quite spread out, as well as the 250m right position which also has its measured directions scattered around and not grouped together like other measurements. Additionally, for each left position, a single strongest signal was found to come from the left most side of the measured direction. This phenomena could be explained by reflections from passing vehicles.

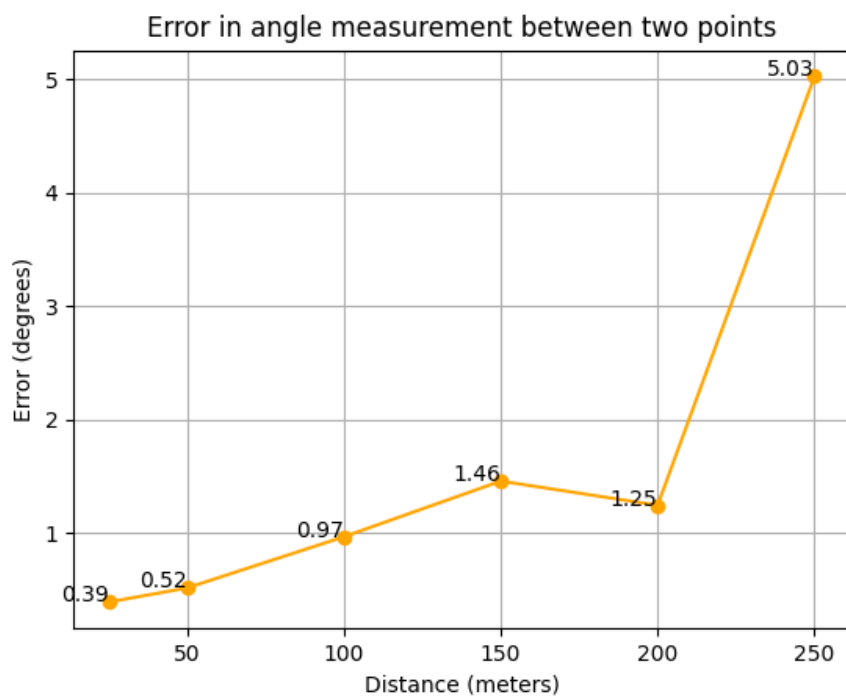


Figure 11. Error in angle measurement between two points.

The angle between the measured average directions of left and right positions at each distance, which was calculated by adding up the angle to both measured average directions from the center line, was used to find the measured angle between both points. This average measured angle was compared to the accurate real calculated angle from known

positions, to find the error at which the drone detector performs direction finding, which can be observed at Figure 11. It can be deduced that as the distance to the two positions at which the drone simulator's direction was measured, the error between measured and real angle increases. While from 25m to 200m, the error remains below 2 degrees, at 250m the error increases to over 5 degrees. It is also important to note again that at further distances, the transmission power of the drone simulator was increased. The increase at 250m can thus not be attributed to low signal strength, as can be observed in Figure 11, which depicts the average received signal strength of each position at which measurements were taken.

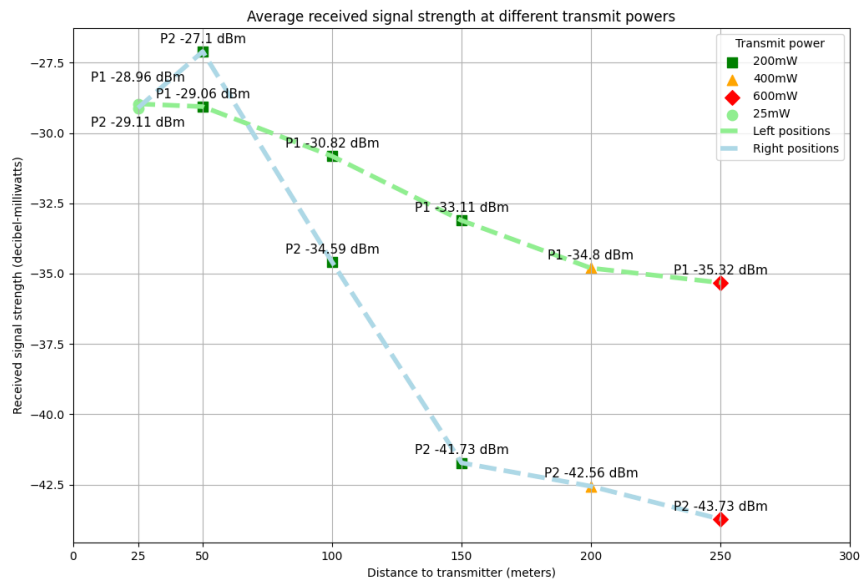


Figure 12. Measured average received signal strength.

The green dashed line on Figure 12 shows the received signal strength of the left positions, while the blue denotes the same for the right positions. At each position at which the drone simulator was placed, the transmission power at which the drone simulator transmitted the video signal is shown. At 25m, the transmitter was set to 25mW. From 50m to 150m

the transmission power was increased to 200mW, at the 200m positions the transmission power was at 400mW, while the 250m measurements were done with the drone simulator transmitting at 600mW power. As the distance to drone simulator increases, from Figure 12 it can be seen that the received average signal strength of the left positions decreases less than it does for the right positions.

5 Discussion

The small average error for angle measurements in Figure 11 can be seen as a positive outcome. Furthermore, because two positions were measured, it can be said that each position's own average measurement error ranged between 0 degrees and the measured average angle error. This means that for example, at 100 meters, the average error at which a single position can be measured is between 0 degrees and 0.97 degrees using this low-cost method for direction finding.

Based on Figure 10, the measurements taken at error testing were relatively well grouped together, within around a 10 degrees angle. It is interesting to note that the found directions were similarly grouped together at almost all of the distances. This can be attributed to the directional antenna's gain being relatively similar over an area at the front of the antenna, as stated in the parameters of the antenna earlier that the beam width at the front of the antenna is around 30 degrees. This means at around a small angle at the front of the antenna, signals within a few degrees can have almost the same received signal strengths. This, in conjunction to variations in incoming signal's strength, possibly due to how the PAL encoded signal's amplitude changes, meaning that multiple scans at the same direction can have variations in signal strength, would explain the spread of the measured strongest signal directions. For example, if the drone locator's antenna was pointed directly at the signal source and the signal was captured, then moved a portion of a degree in some direction, the amplitude of the signal might be higher for the new measurement and with relatively similar antenna gain at both measurement points, the new position might have a higher measured signal strength than the position where the directional antenna was directly on the drone simulator. Thus over a certain angle, measured strongest signal directions can differ due to the antenna construction and the variation of the measured signal over time.

The reason why in Figure 10 at 25m the left measurement point's strongest signal

directions are spread out can also be attributed to the measuring directional antenna having its beam width similar at close range. Additionally, reflections from passing cars could have caused the spread at the 25m left position, as the drone detector was close to a road which was to the left of the left positions. Reflections from passing vehicles could also have caused some strongest signal direction measurements to be found at the 22.5 degree area for each left position in Figure 10. For the 250m right position, spread of the measurements can be attributed to the high grass partly obscuring the line of sight between the drone detector and the drone simulator. Additionally, variations in the height of the field could have caused the 250m right point's drone simulator to be placed higher than the drone detector's antenna was pointed. These two variations might have been the cause for the spread of found strongest signal directions. This spread at the 250m right position can be attributed as the reason why in Figure 11 the error at 250m had a sharp increase compared to other distances.

Regarding the difference in average signal strengths in Figure 12, the tall grass might have caused the degradation of the average received signal strength for the right positions. During testing, the drone simulator had its antenna barely above the grass. This might have caused dissipation of the signal's energy as the tall grass might have obstructed a part of the signal meant to reach the drone direction finder. Additionally, it is possible that the field might have had a slight incline, and thus as further away the right positions got from the drone detector, the drone simulator's antenna was higher relative to the detector's horizontally level directional antenna. As the drone simulator was placed further away, the scanning directional antenna's center would be off-center from the drone simulator's emitted signal. While the strongest signal direction was still possible to be found with similar accuracy as the left positions, the overall strengths of signals measured on the right side decreased.

Maximum range at which the drone detector can detect a drone was not measured, as the

thesis focuses on feasibility and the accuracy of finding the direction of the FPV drone signal. This is the reason why at longer ranges, the drone simulator's transmission power was increased, as it allowed for measurements which enabled error calculation with greater confidence. The FPV drones, whose emission direction would be determined, would not have their transmission power known by the drone locator. This, in addition to the variability in the possible gains at each step of the signal capture and processing, means determining the distance to the FPV drone would vary greatly if received signal strength was used to estimate distance to a transmitter. In future works, this could be investigated, along with other methods for determining the range or the position of an FPV drone - one way would be to use multiple drone detectors of similar construction and find the position of the FPV drone by combining the directions found by each detector. As such, distance and position estimation and maximum detection range determination were considered out of scope.

In this thesis, vertical angle measurement error was not tested. The method used for horizontal error testing could be used to determine the vertical angle measurement error. To achieve this, positions high up would have to be used. Due to not having access to full FPV drones, such measurements were not performed. Additionally, as there is no difference in the way the antenna can move using the servo system if vertical or horizontal axis are considered, a horizontal-only test was considered representational of the measurement error of the system. However, in the future a combined measurement of horizontal and vertical error could be explored.

In the future, the speed at which the scanner can cover positions around it could also be focused on. For example, one way to improve the speed would be to change the way scans are taken, as currently the system moves to a position after which it performs a measurement, doing this in a repeating pattern. In future works, instead a method could be devised where the scanning system constantly performs rapid scans while the servo

system moves the antenna at a pace, such that the desired amount of scans per one degree is maintained.

Additionally this project could be expanded by developing the GUI application further to support real-time tracking of a found FPV drone signal, as currently the system only takes measurements and determines the direction at which the strongest analog video signal was found from. Signal identification and classification could also be explored to differentiate FPV drone video signals from other analog video signals which in reality could occupy the same frequencies as the FPV drones operate on.

Conclusion

The increased widespread use of fast-flying first-person view drones has highlighted the need for affordable detection systems to address the risks they pose, such as physical harm and privacy violations. Current detection systems are often costly or inaccessible, thus a more economical solution for locating these drones is needed. In this thesis, the feasibility of a low-cost solution for the direction finding of first-person view drones by their radio emissions has been thoroughly explored.

An overview was given of first-person view drones, their radio emissions and transmission systems. Methods for signal direction finding were covered, as well as radio devices capable of measuring signals transmitted by first-person view drones. FPV drone's video signal was identified as the emission which should be tracked. Based on the acquired knowledge, a mechanically-actuated scanner utilising a directional antenna and a software-defined radio device was designed. The device was built with components selected based on research done in this thesis. For assembly, structural components were modeled and 3D printed. A user-friendly GUI program was designed and written for visualising incoming signals, along with code for processing said signals.

Results showed that an affordable system for direction-finding could be constructed. Evaluation of the designed system showed little average error when determining the direction of a first-person view drone's video signal emissions. Tests were done at distances ranging from 25m to 250m over clear and slightly obstructed conditions. Thus the system can confidently perform direction-finding tasks. The system was considered an affordable solution when compared to existing products.

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Appendix

I. Drone Simulation Hardware

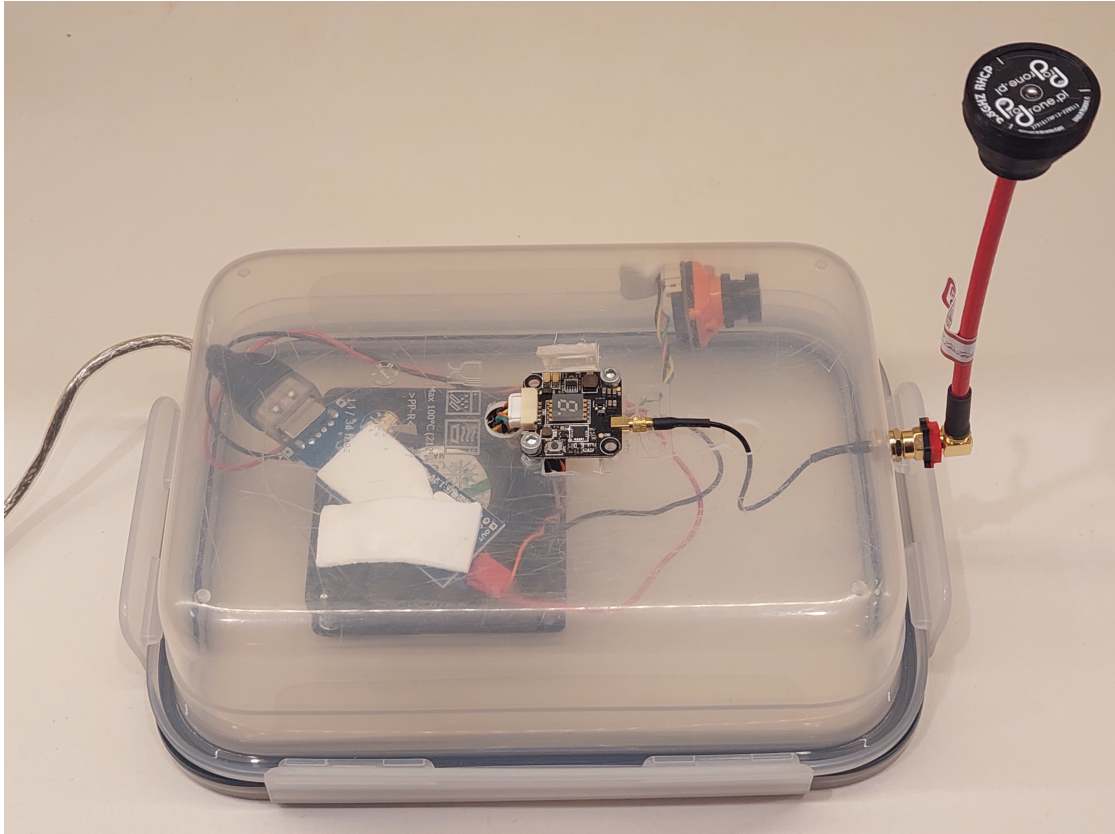


Figure 13. Drone simulation hardware.

II. Field Used for Testing



Figure 14. The detector on the field which was used for testing.

III. GitHub Repository

The GitHub repository of this thesis: <https://github.com/peregrinefalc0n/drone-locator>.

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