Abstract—Technological evolution has enabled the emergence of new platforms in the aeronautical world. In this context emerged the unmanned aircrafts called Unmanned Air Vehicle (UAV).

UAVs emerged as a very versatile and economical tool so, its applications, besides being directed to the military world, also have civilian application. The Portuguese Air Force is the Armed Forces branch that, currently, most explores the various applications of these devices. However, the Portuguese Army and the Portuguese Navy have been investing in the acquisition of these devices for applications as reconnaissance missions or control of the Portuguese coast.

The potential of this tool has been developed in such a way that autonomy and range have increased significantly. But, when the data transmission is improved it is also necessary to improve communication systems.

The present work describes the development of a "smart" antenna for application in this type of platforms. This antenna (ESPAR antenna) allows the control of the direction of the main lobe of the radiation pattern, to ensure communication to the base station (EB). It uses a planar antenna array with frequency of 1.33 GHz, whose first version was designed and constructed previously.

After designing the planar ESPAR antenna, a control system was developed to integrate the communication system. This consists of an antenna coupled to the control system. The control system consists of an arduino and a digital potentiometer, and the algorithm installed redefines the direction of the radiation lobes as a function of flight needs.

The ESPAR planar antenna was tested in the anechoic chamber with the control system coupled to it, so that all previously established requirements were validated.

Index Terms: P-ESPAR Antenna, Smart antenna, Control System, Arduino, UAV Communication system.

I. INTRODUCTION

The Ministry of National Defense has, as priorities in its investment and development program, the areas associated with the command, operation and supervision of the Armed Forces (AF) [1]. These perspectives are in line with those of the other industrialized countries, that intends to carry out a transformation in the Defense area, that aims to modify the current forces, transforming them into forces based on knowledge and sophisticated technological platforms [2].

Operational Theaters (OT) are increasingly demanding and AF have realized that we have entered the information and knowledge age, where information plays a decisive role in achieving operational superiority. Operations are increasingly focused on obtaining information, in order to anticipate the enemy forces movements and objectives and gain advantages in decision making [2].

Therefore, the Armed Forces need fast, flexible forces with good communication systems and the battlefield monitoring capability [1]. With this objective, the investigation and development of means by the Armed Forces, intends to maximize the effectiveness of its forces. A great bet of the same goes through the UAVs. This technological environment is used in a military context due to its flexibility and capacities of projection and exploration in the field, and in some situations, it can replace conventional aircrafts. As such, UAVs are applied for example to missions in environments with chemical or biological contamination and hostile missions of high risk. These missions are called missions D3 - Dull, Dirty and Dangerous. These devices are also used when the commander believes it necessary, both from a tactical and economic point of view, which makes the UAVs an attractive tool for the military context [1].

II. THE STATE OF ART

A. Contextualization of the UAV

Unmanned vehicles (UVs) are used on all types of surface (water, air and land) [3],[4]. The following illustration represents the classification of UVs, divided by action.

![UV classification by field of performance](image)

Figure 1 UV classification by field of performance

The UAVs used for military applications present greater robustness and reliability than a UAV used for civil applications. Factors such as weight, size, volume and input power are important in the construction of a UAV [4].

One of the many applications of UAVs is the Electronic Warfare (GE). "Electronic Warfare” can be defined as the set of actions that use the electromagnetic energy to neutralize the opponent's command and control ability; that take advantage of the use of the electromagnetic spectrum
by the enemy; which ensure efficient use of the electromagnetic emissions of friendly forces" [5].

Regarding GE, it is easily found utility in UAVs. The aircrafts allow an approach to the enemy forces, to interfere in his entire communications network. The objective is to use the UAVs to replace the traditional vehicles, improving the efficiency of the interference, reducing the costs and increasing the speed and safety of their own forces [5].

With the existence of several applications, it becomes necessary to study the communication system of the UAV to increase the range and improve the efficiency of the connection.

B. Communication Systems

Currently the UAVs have incorporated a communication system capable of providing data to the Base Station (EB) such as location, image and information of the conditions of the device. The communication between the UAV and the EB must be bidirectional, since it is also necessary to send control information from the Base Station to the UAV [6].

Antennas are passive devices that, in a wireless system, are the forefront of emitters and receivers, presenting three fundamental properties: gain, directivity, and polarization. Given their passive characteristic, the antennas redirect the energy they receive from the emitter to a certain direction, directional antennas, or radiate uniformly in all directions, omnidirectional antennas [7].

In the case of UAVs, the antennas are dimensioned according to the needs of the aircraft, and the project is still limited by aerodynamic characteristics. The weight and the robustness are fundamental characteristics, mainly in UAVs for military application.

The antennas normally used for this purpose are planar antennas, whip antennas and loose wire antennas. Planar antennas are the most used, since they can be used as omnidirectional antennas or directional antennas, which make them very flexible. At the aerodynamic level, they do not interfere significantly with the structure.

Whip antennas, despite their low cost, have aerodynamic problems and a low gain, these are classified as omnidirectional antenna. Finally the loose wire antenna, which despite its high gain allow a greater range, sees its use limited by the aerodynamic slope and risk of damage in the UAV [4].

Figure 2 a) Planar antenna [4] b) Whip monopole antenna [4] c) Dragged Wire Antenna [4]

The antenna to be studied is the planar antenna, because it allows a change in the main lobe of propagation of the electromagnetic energy and because it improves the aerodynamic behaviour of the aircraft, being this a crucial factor.

Planar antennas are antennas used when the antenna design constraints require reduced size and weight, low cost and high efficiency.

The main parameters that should be considered in the project of this antenna are: the relative dielectric constant of the substrate, (\(\varepsilon_r\)); the thickness h of the substrate and its size; the patch configuration, and the patch dimensions. These characteristics determine the radiation pattern of the antenna. Figure 3 shows a planar antenna with the above-mentioned characteristics noted.

Figure 3 Specification of a planar antenna [8]

The feeding method used in the antenna design was the line feed method, given the simplicity and ease of input impedance matching.

One of the several types of planar antennas are the ESPAR antennas. These antennas allows to adapt the direction of radiation, constituted by N elements, where one element is active and the other are passive elements coupled to the active. The mutual coupling is created by changing the spacing between the elements of the ESPAR antenna array and using reactivities coupled to the passive elements [9].

The ESPAR antenna uses the mutual coupling to excite the parasitic elements. These elements are charged according to a variable reactance origined by varicap diodes. The variation of the value of the reactances is reflected in the alteration of the main lobe of the radiation diagram [10]. The process of changing the main lobe is called beamforming.

Unlike conventional antennas, the ESPAR antenna does not have individual lines for receiving / transmitting because only one antenna element is connected to the circuit. The ESPAR antennas are an increasingly used solution because it allows beamforming, i.e. switching the main lobe maximizing the received signal and minimizing interference [11].

This article will present the construction of an intelligent antenna for a UAV using this technology.

III. P-ESPAR ANTENNA STUDY

In this article we will present the development of a low-cost prototype of a P-ESPAR antenna with two layers of air and one layer of FR-4. This antenna arises in the context of an earlier dissertation, where the design of an antenna with substrate RT Duroid 5870 was carried out by Alferes Marques.

In this sense, the configuration and simulation of the antenna will be presented as well as the conclusions regarding the comparison of the results obtained through the CST Microwave Studio simulator.

The sizing of the P-ESPAR antenna took as mandatory requirements the parameters presented in Table 1.
Table 1 Requirements for antenna design P-ESPAR

| Requirement                  | Requirement Value |
|------------------------------|-------------------|
| Frequency                    | 1.330 GHz         |
| Gain                         | > 3 dB            |
| Bandwidth                    | > 8 MHz           |
| Coefficient of reflection $|S_{11}|$ | ≤ -10 dB |

A. P-ESPAR Antenna configuration

The developed P-ESPAR antenna consists of an aggregate of three elements, the middle element being the active element and the remaining parasitic elements. The three elements have the same dimensions. The antenna has a resonance frequency of 1.33 GHz.

The choice of substrate was a choice conditioned by economic reasons. Initially, the chosen substrate was the RT Duroid 5870, but given its high cost, the prototype of the antenna was constructed with a substrate composed of two plates of FR-4 and an air layer of a thickness that allows to obtain a structure with the same constant ($\varepsilon_r$), its homogeneity, the tangent of the loss angle (tan$\delta$) and the thickness (h). In the equivalent model, it is accepted that it has the same characteristics of RT DUROID 5870, but with a different thickness. For this reason, the patches have been resized, the antenna simulation work repeated and, therefore, other coupling diodes chosen, so that the antenna is perfectly adapted to the design requirements.

The antenna was constructed to present the same dielectric constant equivalent of RT Duroid 5870, for which two FR-4 substrates with one layer of air were used between them to approximate the dielectric constant to the Duroid RT 5870 values. Table 2 shows the characteristics of the FR-4 substrate and the Duroid 5870 RT for antenna sizing.

Table 2 FR-4 and RT Duroid 5870 substrate specifications [12],[13]

| FR-4 | RT Duroid 5870 |
|------|----------------|
| $\varepsilon_r$ | 4.700 | 2.230 |
| $\varepsilon_r$ | 2.330 | 2.330 ± 0.020 |
| tan$\delta$ | 0.014 | 5.000e-5 |
| Espessura | 1.575 mm | 1.575 mm |

After choosing the substrate, the dimensions of the P-ESPAR antenna patch were calculated. Then the values of these dimensions were optimized using a CST Microwave studio software optimization tool. Table 3 shows the values obtained from the sizing and subsequent optimization, and it is also possible to observe the value obtained for the resonance frequency in table 4.

In Figures 4 and 5 it is possible to identify the calculated dimensions with their location on the P-ESPAR antenna.

Table 3 Dimensions of the antenna with two substrate FR-4 plates and one layer of air

| Dimensionamento | Otimização |
|-----------------|------------|
| Patch Width     | W          | 87.400 mm | 84.300 mm |
| Patch Length    | $L_p$      | 71.760 mm | 65.600 mm |
| Antenna Length  | $L_{ant}$  | 274.900 mm | 274.900 mm |
| Width of transmission line | $W_e$ | 3.500 mm | 4.500 mm |
| Substrate Thickness | h | 1.575 mm | 1.575 mm |
| Ground thickness | $h_g$ | 0.019 mm | 0.019 mm |
| Thickness of air layer | $h_{ar}$ | 1.090 mm | 1.090 mm |
| Total thickness | $h_{total}$ | 4.240 mm | 4.240 mm |
| Diode Length    | $G_d$      | 3.000 mm | 3.000 mm |
| Position of mutual coupling of the diode | $O$ | 30.000 mm | 30.000 mm |
| Insert feed point location | $y_s$ | 22.842 mm | 20.000 mm |
| Resonance resistance | $R_e(y = 0)$ | 105.403 Ω | 105.403 Ω |
| Input resistance for insert insert feed | $R_{ins}(y = y_s)$ | 50.000 Ω | 50.000 Ω |
| $x_s$ | 6.000 mm | 6.000 mm |
| $L_c$ | 44.500 mm | 44.500 mm |
Table 4 Frequency of resonance

| Two layers of FR-4 with one layer of air |
|-----------------------------------------|
| \((f_r)_{010}\) | 1.368 GHz |
| \((f_c)_{010}\) | 1.330 GHz |

B. Equivalent Circuit

The planar antenna, from the point of view of the excitation signal source, can be described by an equivalent circuit, for example a parallel RLC circuit, as shown in Figure 6.

![Figure 6 Equivalent circuit of planar antenna [15]](image)

To determine the value of \(R\), \(L\), and \(C\) is necessary to carry out the study of the equivalent circuit, i.e., it is necessary to study the value of the current \(\dot{I}\) represented through:

\[
\dot{I} = \frac{V}{R + j(\omega L) - \frac{1}{\omega C}}
\]

To maximize the antenna current module \(I_{\text{max}}\) is necessary that the imaginary component of the previous equation be equal to zero:

\[
(\omega L) - \frac{1}{\omega C} = 0 \Leftrightarrow \omega = \frac{1}{\sqrt{L C}} \quad \text{sendo} \quad \omega = 2\pi f
\]

After the analysis of the previous equation it is noticed that the \(L\), \(C\) are dependent on the resonant frequency of the antenna.

In the case of this antenna the variation of the radiation lobe is dependent on the capacitances of the varicap diodes. These diodes add a capacity to the \(2C_T\) as shown in figure 7 [15].

![Figure 7 Equivalent circuit of P-ESPAR antenna [15]](image)

Before an analysis to the system of equations it is necessary to realize that \(C_{\text{eff}} \neq C_T\), that is, \(C_{\text{eff}}\) corresponds to the value of the effective capacity of the diodes in the circuit. This value is directly dependent on the positioning of the diodes in the patch as represented in the following equation and figure 8, where the variables \(O\) and \(L\) are represented [15].

\[
C_{\text{eff}} = C_T \cos^2(\pi\theta) \quad \text{sendo} \quad \omega = 2\pi f
\]

![Figure 8 Representation of variables O and L in the patch](image)

In the case of the equivalent circuit of the antenna, with the integration of the diodes, it is necessary to change the equivalent capacity, since capacity \(C\) is added to the capacity of the diodes. The following equation represents this change.

\[
(\omega L_c - \frac{1}{\omega C}) = 0 \Leftrightarrow \omega = \frac{1}{\sqrt{L_c(C + 2C_{\text{eff}})}}
\]

To determine \(L\) and \(C\), the CST Microwave studio simulator was used to obtain the resonance frequency values of the antenna without and with diodes, respectively \(f_0\) and \(f_c\). The capacity of the diodes considered for simulation purposes is \(C_T = 1\mu F\). The system of following equations allows \(L\) and \(C\) [15].

\[
\begin{align*}
2\pi f_c &= \frac{1}{\sqrt{L_c C}} \\
2\pi f_c &= \frac{1}{\sqrt{L_c(C + 2C_{\text{eff}})}}
\end{align*}
\]

Results:

Table 5 Results obtained for the calculation of \(L\) and \(C\)

| Two layers of FR-4 with one layer of air |
|-----------------------------------------|
| \(f_0\) [GHz] | 1.388 |
| \(f_c\) [GHz] | 1.383 |
| \(O\) [mm] | 31.000 |
| \(C_{\text{eff}}\) [pF] | 0.065 |
| \(L_c\) [nH] | 2.668 |
| \(C\) [pF] | 4.932 |

After obtaining the results of \(L\) and \(C\) of the RLC circuit, it was necessary to calculate the value of the resistor \(R\). Thus, an analysis was made to the circuit, considering that the relation between the complex amplitude of the
current in the resistor \( I_r \) and the complex amplitude of the total excitation current \( I_{exc} \), at where \( G = \frac{1}{R} \).

\[
\frac{I_{r}}{I_{exc}} = \frac{G_{r}}{G_{exc}} * \frac{V}{V} \Rightarrow \frac{I_{r}}{I_{exc}} = \frac{G_{r}}{G_{exc}} + j(\alpha L_{r} - \frac{1}{\omega C_{r}})
\]

Initially, it was established that the reflection coefficient \( S_{11} \) cannot exceed -10dB. For this reason, the ratio in dB between the complex amplitude of the current in the resistance and the complex amplitude of the total current can not be greater than -10dB as represented in the following equation. This equation is solved to \( R \) to obtain the resistance value.

\[
-10 = 20\log \left| \frac{1}{1 + j(\frac{\alpha L_{r}}{G} - \frac{1}{\omega C_{r}})} \right| \Rightarrow \frac{1}{\sqrt{10}} = \sqrt{1 + \left(\frac{\alpha L_{r}}{G} - \frac{1}{\omega C_{r}}\right)^2} \Rightarrow \text{onset} G = \frac{1}{R}
\]

Final Results:

Table 6 Values obtained from the RLC equivalent circuit

| Two layers of FR-4 with one layer of air |  |
|----------------------------------------|--|
| R [kΩ] | 1.608 |
| Lc [nH] | 2.668 |
| C [pF] | 4.932 |

To study the coupling, it is necessary to consider the dielectric loss quality factor \( Q_d \), the antenna patch quality factor \( Q_a \), the metal loss quality factor \( Q_m \) and the quality factor of antenna radiation \( Q_{rad} \), represented by the following equations. The variables a, b, W and L are represented in figure 9 [16],[17].

\[
Q_d = \frac{1}{\tan \delta}
\]

\[
Q_a = \frac{C_{a}Q_{a}}{Q_{a} + Q_{d}}
\]

\[
Q_{rad} = \frac{I_{r}^{2} \varepsilon_{v}}{32\pi \sin(\frac{\pi W}{2a})} \frac{bZ_w}{a}
\]

\[
\varepsilon_{v} = \text{Permittivity of vacuum} \rightarrow 8.85418782 * 10^{-12}
\]

\[
Z_w = \text{Impedance} \rightarrow 50 \Omega
\]

Figure 9 Variation of the magnetic field in the substrate for the fundamental mode [16]

Analyzing the quality factor of the dielectric it is perceptible that it depends on the loss tangent \( \tan \delta \) of the same. In the case of the antenna with the FR-4 substrate the medium is not homogeneous, that is, there are 3 media with different values of \( \tan \delta \). As such, it is necessary to calculate the value of the equivalent loss tangent \( \tan \delta^* \).

To perform the study of the tangent of losses it is necessary to establish the equivalent circuit for the substrate as shown in figure 10. Each substrate corresponds to a parallel RC circuit, whereby the 3 underlying substrates correspond to the series of these circuits as represented.

For calculating \( \tan \delta^* \) it is necessary to take into account the W, L, h, and a of each substrate.

Figure 10 Representation of the equivalent circuit of antenna substrates with FR-4 [17]

The antenna resembles a 3-component system, whereby the \( \tan \delta^* \) for these circuits is given by the following equation [18],[19].

\[
\tan \delta^* = \frac{C_{C_{a}}\tan \delta_{a} + C_{C_{b}}\tan \delta_{b} + C_{C_{c}}\tan \delta_{c}}{C_{C_{a}} + C_{C_{b}} + C_{C_{c}}} = \frac{\text{com}C = \varepsilon_{v}e_{r}^{*}W*L}{h}
\]

Table 7 Parameters and results

| \( \tan \delta_{a} \) | 0.014 | \( L_{1} = L_{2} = L_{3} \) | 274.900 mm |
|------------------|-------|---------------------|-----------|
| \( \tan \delta_{b} \) | 0.000 | \( h_{1} = h_{2} \) | 1.575 mm |
| \( \tan \delta_{c} \) | 0.014 | \( h_{2} \) | 1.090 mm |
| \( \varepsilon_{r_{1}} \) | 4.700 | \( C_{0} = C_{0} \) | 0.725 nF |
| \( \varepsilon_{r_{2}} \) | 1.00059 | \( C_{0} \) | 0.220 nF |
| \( W_{1} = W_{2} = W_{3} \) | 99.820 mm | \( \tan \delta^* \) | 0.00528755 |
After you have calculated the \( \tan \delta' \), all conditions are met to calculate the quality factors and then evaluate the antenna coupling. Thus, the coupling conditions are as follows [16]:

1) \( Q_{\text{rad}} = Q_0 \), critical coupling;
2) \( Q_{\text{rad}} > Q_0 \), under-coupled;
3) \( Q_{\text{rad}} < Q_0 \), over-coupled.

![Figure 11 Variation chart of the antenna coupling as a function of substrate height](image)

The diodes used are the varicap diodes of Infineon BBY53-03W. These have been selected because they are closest to the antenna capacity.

The characteristics of the varicap diodes are shown in table 8.

**Table 8 Characteristics of varicap diodes**

| BBY53-03W | 3.1pF |
|-----------|-------|
| Average variable capacity (\( C_T \)) | 3.1pF |
| Diode Inductance (\( L_S \)) | 1.8 nH |
| Diode resistance (\( R_S \)) | 0.47 \( \Omega \) |

**C. Simulations**

After completing the entire sizing and configuration process of the P-ESPAR antenna, the simulations were performed through the CST Microwave studio software.

To obtain the different azimuths, the combinations of CT1 and CT2 diodes, shown in table 9, were varied in simulator.

![Figure 12 Results obtained with FR-4 to -10°](image)

![Figure 13 Results obtained with FR-4 for -5°](image)

![Figure 14 Results obtained with FR-4 for 0°](image)

![Figure 15 Results obtained with FR-4 for 5°](image)

![Figure 16 Results obtained with FR-4 to -10°](image)

**Table 9 Results of the P-ESPAR antenna simulation with FR-4 using the varicap diodes BBY53-03W**
After analyzing the results of table 9 it was possible to conclude that the requirements imposed were all fulfilled and that all the conditions for the construction and tests are gathered.

IV. CONTROL SYSTEM DEVELOPMENT

The design of the control system was performed according to the antenna constructed, i.e. in this case the control system was scaled according to the P-ESPAR antenna with FR-4 substrate and varicap diodes BBY53-03W.

The change in the direction of the azimuth of the radiation lobe is performed through the variation of the coupling between the elements of the aggregate, that is, through the bias voltages applied on the diodes. This way, a microcontroller and a digital potentiometer will be used. The microcontroller will be the means of communication between the central processor of the UAV and the digital potentiometer.

A. Microcontroller

The microcontroller to be integrated in the circuit has as main function the processing of the data related to the flight of the UAV and, according to these data, send the voltage values corresponding to the communication needs to reverse bias of the diodes that ensures the value of the necessary capacities to the deflection of the antenna lobe. For the performance of this function there are numerous microcontrollers so that, as selection factors, the following parameters were considered:

- User interface;
- Support communication Serial Peripheral Interface (SPI);
- C programming language;
- USB connection;
- Simple and economical.

After analyzing all the possibilities, the chosen microcontroller was the Arduino Uno. In addition to complying with the requirements presented is a microcontroller very tested and present in several platforms, which allows to test in computational environment the expected result.

B. Digital Potentiometer

The digital potentiometer receives the information from the microcontroller and adjusts the desired voltage at the terminals of the diodes. For this, the digital potentiometer varies the value of its resistance and, being the current constant, the output voltage varies. Through the digital communication between the microcontroller and the digital potentiometer it was possible to control the value of the resistance, which in turn controls the voltage value. To select the digital potentiometer, the following factors were considered:

- 2 output channels;
- Package PDIP;
- Interface SPI;
- Much sensitivity in varying the resistance value;
- V_{IN}=5 \text{ V};

After analyzing all possibilities, the selected digital potentiometer was the Microchip MCP42100. This potentiometer has 2 channels, 14 pins, 256 levels and a resistance of 100 kΩ. It operates with voltages of 2.7 - 5.5 V and the communication interface with the Arduino is SPI.

C. Control system circuit

After selecting the microcontroller and the digital potentiometer it was possible to build the control system. For this it was necessary to define 3 ports of the Arduino to establish communication between the microcontroller and the digital controller. The 3 selected ports were the Arduino digital ports 10, 11 and 13, where port 10 is the port responsible for the activation and deactivation of the potentiometer, port 11 is responsible for communicating data relating to the SPI interface and port 13 is the port responsible for clock synchronization.

This way, the port 10 is connected to the pin 1 which is the pin responsible for activating or deactivating the digital potentiometer, the port 11 to the pin 3 which is the pin responsible for collecting data and the port 13 to the pin 2 which is the pin responsible for clock synchronization of the digital potentiometer. The remaining pins are connected to ground and 5V from the Arduino as designated in the datasheet. Figure 16 corresponds to the circuit diagram of the control system circuit.
D. Control Algorithm

The P-ESPAR antenna control system was delineated by a set of criteria. These criteria were established by the needs that the communication determines according to the flight route of the UAV. In this way, the algorithm defines by degree of priority the variation of the lobe and finally the change of the route of the UAV.

The behavior of the P-ESPAR antenna was one of the main criteria of the algorithm. In a first phase, it was necessary to realize the capacity of the lobe to change the antenna radiation to perceive how necessary it will be to influence the route of the UAV. However, the orientation and inclination of the UAV according to the various axes are also a very important factor to be considered by the algorithm of the control system.

The procedures related to the algorithm mechanism are presented in figure 17 and in the procedure presented below.

1) Control system communicates with the central processor of the UAV to request the coordinates of the base station;
2) After receiving the coordinates of the base station, the control system communicates again with the central processor of the UAV and requests the current coordinates, the inclination and the height of the UAV;
3) After receiving current coordinates, the control system algorithm calculates the distance between the UAV and the base station;
4) If the distance is less than or equal to 40 km the control system selects the slope that least interferes with the route of the UAV and calculates the minimum variations required for its route;
5) The control system communicates with the central processor of the UAV, sending information about its orientation and positioning. According to the base station the UAV must be perfectly perpendicular and parallel to the ground. It also sends information on changing the slope of the UAV;
6) After changing the route according to the communication needs, the algorithm checks the combination of capacities relative to the angle of the selected radiation lobe and the control system communicates with the digital potentiometer to inject to the terminals of the diodes the corresponding voltages;
7) After completing the previous steps, the necessary conditions for the transmission of 10 seconds are fulfilled. At the end of the transmission, we return to step 2).

V. CONSTRUCTION AND IMPLEMENTATION OF SMART ANTENNA

A. Smart antenna construction

The implementation of the communication system was carried out in two phases: antenna construction; construction of the control system.

The P-ESPAR antenna was built in the laboratories of the Instituto Superior Técnico with the support of the technician Mr. Carlos Brito who accompanied the entire construction process, and whom we thank.

![Figure 19 Presentation of the P-ESPAR antenna built in the frontal perspective](image)

![Figure 20 Presentation of the P-ESPAR antenna built from the rear perspective](image)
The circuit was printed in the IST field at Taguspark with the support of the technician Mr. Pina, whom we thank. The circuit uses three cable terminal board ports with three outputs, these being used as terminals of the digital potentiometer.

![Figure 21](image1.png)  
Figure 21 Representation of both sides of the built circuit

### B. Experimental results

The experimental results were obtained in the anechoic chamber of the scientific area of the Institute of Telecommunications of the IST, reason why by technical limitations were only available conditions to measure the $S_{11}$ and the radiation diagram.

The combinations of the diodes used can be observed in table 10.

| CT1 | CT2 |
|-----|-----|
| [pF] | [V] | [pF] | [V] |
| -5º | 2.70 | 2.65 | 2.00 | 5.00 |
| 0º  | 2.60 | 2.80 | 2.6 | 2.80 |
| 5º  | 2.00 | 5.00 | 2.70 | 2.65 |

Figure 22 Representation of $|S_{11}|$ with variation of 0º ±5

Starting with the analysis of the $|S_{11}|$ parameter, it is possible to verify that the resonance frequency is very close to the frequency on which the antenna design was carried out, that is, the measured value was 1.41GHz, and the antenna was dimensioned for 1.33 GHz. To correct this small deviation, it would be necessary to study the behavior of the resonance frequency with slight changes of the distances in the patch.

Regarding the tax requirement of $|S_{11}| \leq -10$ dB, this was not observed in the results obtained through the network analyzer. In the results obtained through simulator, the requirement was always fulfilled with a comfortable margin, so it would be necessary to correct the height of the air layer and to verify through the network analyzer the variations of the parameter $|S_{11}|$. The height of the air layer is not constant throughout the antenna since it is impossible to obtain the accuracy imposed by the simulation.

![Figure 23](image2.png)  
Figure 23 Representation of the radiation diagram for 0º in the H plane

![Figure 24](image3.png)  
Figure 24 Comparison of the radiation diagram to ± 5º in the H plane

![Figure 25](image4.png)  
Figure 25 Representation of the radiation diagram for 0º in the E plane

![Figure 26](image5.png)  
Figure 26 Comparison of the radiation diagram to ± 5º in the E plane
In addition to the hg correction, there is still interference caused by power cables with a length approximately equal to $\lambda / 2$. During the scanning from 0 to 2 GHz it was possible to observe the interference caused by the cables.

Analyzing the radiation diagram, it was possible to verify that the radiation lobe of the P-ESPAR antenna was displaced $-6^\circ$ in relation to the expected azimuth. This variation corresponds to the side on which the power cables were placed so that they may be responsible for this small deviation.

In relation to the azimuthal variation of $\pm 5^\circ$ with $0^\circ$ azimuth, extremely positive results were obtained. Analyzing the graph of figure 5-17 it was possible to verify that in relation to the axis of the antenna P-ESPAR, with respect to azimuth $-6^\circ$, it was possible to vary the lobe from $-11^\circ$ to $-2^\circ$.

These results allow to prove that the measured results go against the simulated ones, being that there are integrated elements in the antenna that the simulator does not allow to consider. However, it is possible to improve the results obtained with minor changes to the insulation of the feed paths of the P-ESPAR antenna diodes and reduce the length of the cables of the diode feed system.

Table 11 Conclusions drawn from the tests carried out in the anechoic chamber

| Plane E | Plane H | [S11] | HPBW | Polarization | $f_0$ |
|---------|---------|-------|------|--------------|------|
| CT1 | CT2 | Maximum direction | Maximum direction | $-11^\circ$ | $0^\circ$ | $360^\circ$ | $-8.0$ | Linear | Vertical | 1.41 GHz |
| 1.9 pF | 2.7 pF | $-6^\circ$ | $0^\circ$ | $360^\circ$ | $-8.3$ | dB |
| 2.6 pF | 2.6 pF | $-2^\circ$ | $0^\circ$ | $360^\circ$ | $-8.0$ | dB |
| 2.7 pF | 1.3 pF | $0^\circ$ | $360^\circ$ | $-8.0$ | dB |

IV. CONCLUSION

The FAP is the branch of Army Forces with more knowledge on UAVs in Portugal. The algorithm integrated in the Arduino was based on the orientation methodology used in the UAVs by FAP. The developed algorithm also uses procedures to change the UAV route, taking into account the limit conditions given by experienced officers in these aircraft. The implemented solution changes the route of the UAV for 10 seconds, whenever the line of sight communication is not possible, i.e. the control system, in this case controlled by an Arduino, changes the flight path of the UAV, if necessary, during the period of time of the communication.

After completing and validating the algorithm of the control system, the P-ESPAR antenna and the electronic circuit were built to integrate the control system.

The P-ESPAR antenna tests were performed in the anechoic chamber of the of the Telecommunications Institute at IST. Through the analysis presented in section V it was possible to conclude that the results were not the same as in the simulator, but rather close. These tests allow to verify the possibility the variation of the lobe of radiation, as well as the adaptation for the dimensioned frequency. It was also possible to conclude which factors were detrimental to the measurements and how to provide the necessary changes.

As previously mentioned, the construction of the antenna with two substrates of FR-4 and an air layer, was an economical option that allowed the dimensioning and development of a prototype. The built antenna is not a final version, but an intermediate step, to demonstrate to the FAP the potential of this solution.

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