Proof of concept for angle of arrival detection system

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This report describes the solution planed to a determined problem consisting in detecting radio-controlled slope soaring airplanes through a gate in races (FAI, F3F discipline). The current method is a judge with a flag, which implies a subjective and slow reaction capability that induces irregular and, hence, unfair mistakes. Therefore, the need of improving the system brings us to design a solution to this problem based on an angle of arrival detection system whose evolution will be exposed in detail going from the development of the first idea to the building of a prototype and projection of further improvement to finally make a commercial product.

Key words: Angle of arrival detection

I. INTRODUCTION

In the field of aeromodelism speed races there is a problem that has not been solved yet. This is the fair detection of the planes when going through a checkpoint or gate, which consists of two poles separated several meters located in a hillside of a valley. The current way of detecting a plane through the gates consists of a judge that raises a flag when the plane goes through. This method is very subjective due to its reliance on the judges capability of alienation of the poles in a large distance and the instant it considers the plane going through them plus its reaction time. This induces an error that is too relevant to be neglected and, besides, might not be the same for all the planes going by. Hence, a solution to this problem is an angle of arrival detection system (AOAS) [1]. This allows all the planes to be detected with the same error, which is considerably reduced compared to the current method. In this case the needed and desired AOAS specs are stated in table I.

Frequency	868 MHz
Transmitter power	10 mW
Min range	200 m
Max angular error	1°
Max latency	100 ms

TABLE I. Desired specifications.

II. BASIS OF THE DETECTION METHOD

The main objective is to detect the time when the transmitter is equidistant to the antennas, that is, when the transmitter surpasses the gate line. At this very point, the sum of the signals received by the two antennas is maximum and the difference between them is ideally zero. This result combined with proper election of parameters can lead to a unique gap corresponding to the conditions that need to be detected. Hence, two output channels are needed: the sum and the difference of the signals received by the antennas.

Consider the system composed by two arbitrary antennas separated a distance l and a mobile transmitter at a certain distance d. Due to the features of the problem faced in this work, it can be and it will be assumed that d is much larger than l. Thus, the calculations will be performed with the parallel rays approximation and the received waves will be assumed plane waves. The system is represented in figure 1.

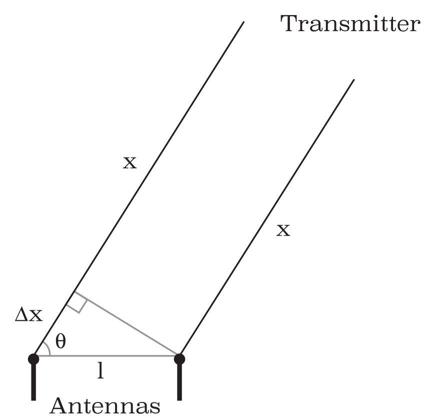

FIG. 1. System with parallel rays approximation

It can be considered that the two antennas receive separately a plane wave of the form e^{-jkx}. Moreover, it can be easily derived that $\Delta x = l\cos\theta$. Thus, the two waves that arrive at the antennas are:

$$E_1 = E_0 e^{-jkx} \quad E_2 = E_0 e^{-jkx} e^{-jl\cos\theta} \tag{1}$$

Where $k = \frac{2\pi}{\lambda}$ is the wave number and x is the distance between the transmitter and the closest antenna. From (1), the sum and the difference can be directly obtained by adding or subtracting the two waves. Accordingly, the resultant wave at the sum channel:

$$\Sigma = E_1 + E_2 = e^{-jkx}(1 + e^{-jkl\cos\theta}) =$$
$$= e^{-jkx}e^{-jk\frac{l}{2}\cos\theta}(e^{jk\frac{l}{2}\cos\theta} + e^{-jk\frac{l}{2}\cos\theta}) =$$
$$= 2e^{jkx}e^{-jk\cos\theta}\cos\left(\frac{l}{2}\cos\theta\right)$$

In the same way, the resultant wave at the difference channel:

$$\Delta = E_1 - E_2 = 2je^{jkx}e^{-jk\cos\theta}\sin\left(\frac{l}{2}\cos\theta\right)$$

Since what will be detected and measured is the power of the waves instead of their fields, their expressions can be written in the following way proportional to $|E|^2$.

$$P_\Sigma = P_{0+}\cos^2\left(k\frac{l}{2}\cos\theta\right) \quad (2)$$

$$P_\Delta = P_{0-}\sin^2\left(k\frac{l}{2}\cos\theta\right) \quad (3)$$

Due to the characteristics of the problem, i.e. a theoretical output of 0 in the difference channel when the target is at $\theta = \frac{\pi}{2}$ rad, it is desirable to avoid fake measures. These correspond to other zeros at the difference channel that should be avoided in the working range of 0 to π rad. This imposes the following condition in the distance l between antennas:

$$k\frac{l}{2}\cos\theta \leq n\pi$$

Which implies:

$$l \leq \lambda \quad (4)$$

Where $\cos\theta = 1$ and $n = 1$ are chosen as worst case scenario.

This condition guarantees $I_\Delta = 0$ only at $\theta = 0, \frac{\pi}{2}, \pi$ rad if $l = \lambda$. Further reduction of the dimension l moves the zeros at 0 and π to the negative plane.

For example, considering $l = 3\frac{\lambda}{4}$, the normalized radiation diagram at each channel can be seen in figure 2

Therefore, it can be concluded that the distance between antennas is a key parameter in the design of this system and should be taken into account in order to avoid fake measures.

III. IMPLEMENTATION

To bring this theory to the field, several components have been used and classified according to their function. Figure 3 represents the system used in this work.

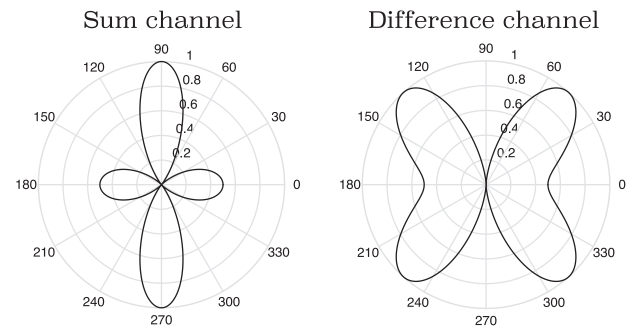

FIG. 2. Theoretical radiation diagrams for each channel in normalized polar coordinates

A. Signal reception and emission

As long as the AOAS is a passive system, it relies entirely in the external emission of the signal meant to be detected. The frequency of the system is 868 MHz due to law and availability [2].

The transmitter antenna is assumed to be a monopole integrated in the target planes. Nevertheless, to execute the proof of concept the transmitter antenna was a synthesizer in a rail.

The antennas used for detection were two vertical parallel folded dipoles separated a distance $3\frac{\lambda}{4}$.

B. Signal combination

As mentioned previously, the key part of the system is the combination of the signal received by each antenna to obtain the sum and the difference between them. This is achieved with a micro-strip 180° hybrid coupler "rat-race circuit" [3] with the desired outputs.

C. Signal conditioning

Due to the system's working frequency there is a lot of noise coming from the television channels and mobile phone's 3G and 4G. Hence, a filter centered in 868 MHz is needed in each output channel of the rat-race circuit in order to avoid constant saturation and reduce the incoming power from undesired signals and noise.

Nonetheless, before the filter there is an amplification stage of 17 dB gain and 3 dB noise figure in order to, according to Friis formula [4], minimize the noise due to the implementation chain and to take more advantage of the detector's dynamic range.

Since the receptor antennas have an omnidirectional radiation diagram around their deployment axis, they make the whole system vulnerable to situational interferences. To achieve more environmental independence,

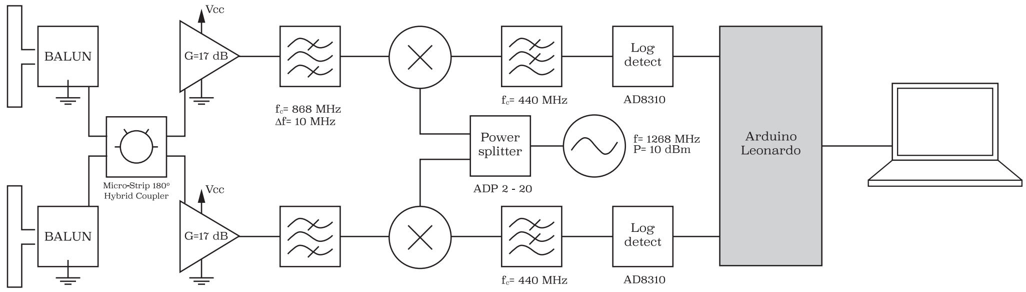

FIG. 3. Block diagram of the system

a metallic mesh was placed behind the antennas to increase their directivity and reduce the interferences from the system itself and its surroundings.

D. Signal acquisition

The resulting signals are detected with a logarithmic detector with a theoretical dynamic range that goes from 10 to $-95dBm$ working in frequencies between 0 and 400 MHz.

Since the AOAS works at 868 MHz the need of changing the frequency of the signal appears. This is solved with a mixer set at 1268 MHz to obtain the desired 400 MHz signal.

The digitalization of the signal is done by means of an Arduino Leonardo board that sends the results to a computer to be processed with MATLAB.

IV. RESULTS AND DISCUSSION

A. Theoretical results

Two main simulations have been performed in order to prove that the chosen components meet theoretically the desired specifications. To do so, the transmission equation must be used [5].

$$\frac{P_r}{P_t} = \frac{G_r G_t}{L} \left(\frac{\lambda}{4\pi R}\right)^2 \tag{5}$$

Where P_r is the received power, P_t is the transmitted power, G_r is the gain of the receptor antenna, G_t is the gain of the transmission antenna, λ is the wavelength, L is the total attenuation and R is the distance between the transmitter and the receiver.

Assigning values to the parameters involved in equation (5) to compute the received power at the antennas, (2) and (3) can be used to obtain the output power at each channel as function of the arrival angle. As a result, the sum and difference outputs can be computed. Figure 4 shows the theoretical outputs for $P_t = 10\ dBm, G = 17\ dB, G_r = 3/2, G_t = 5, L = 2$ and $R = 10\ m$

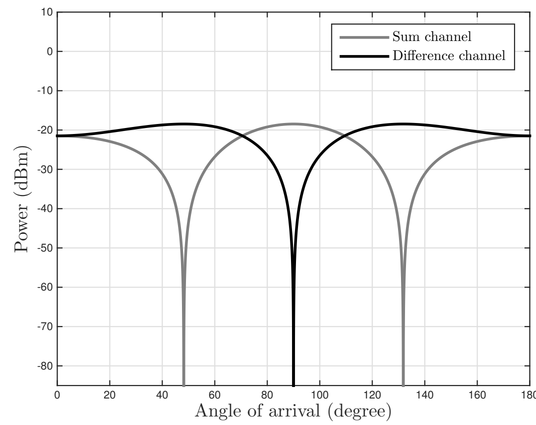

FIG. 4. Theoretical received signals

From figure 4 it is easy to see that there is a positive gap for P_Σ/P_Δ that is unique for $\theta = 90°$. Considering a maximum error in angle of 1°, this gap can be computed as $P_\Sigma/P_\Delta = 27.5\ dB$ for this set of parameters. Moreover, taking into account the limits of the detector and changing the value of R, it is possible to determine which is the maximum distance at which is possible to keep the desired angular resolution. Notice that the pattern does not change over distance, it just moves down on the graphic due to the loss of power and, thus, the gap remains constant. Using this set of parameters and a dynamic range from 10 to $-85\ dBm$, $R_{max} > 200\ m$. This already fulfills the desired specifications, even though the efficiencies are not the most optimistic ones.

B. Experimental results

The diagrams of the E field from each channel were measured in an anechoic chamber just at the output of the rat-race circuit. The antenna was radiating at 10 dBm at a distance $R = 10\ m$ from the device placed on a rotor. The experimental diagrams can be seen in figure 5. Notice that the diagrams are almost limited to 180° due to the metallic mesh.

The key measure of this proof of concept was to try

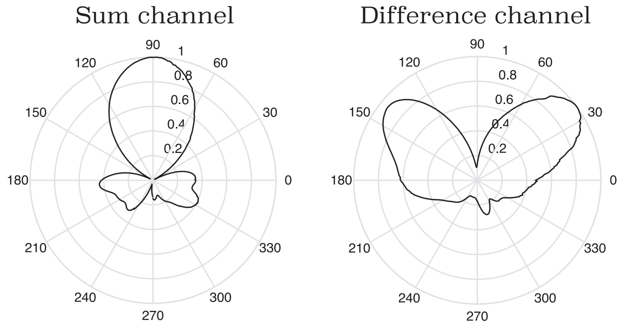

FIG. 5. Experimental radiation diagrams for each channel in normalized polar coordinates

to detect when a moving target surpasses the gate (i.e. $\theta = 180°$) with the AOAS. The setup of the experiment consisted in a straight moving rail with the transmitter antenna separated 3 m from the detection system (maximum possible due to chamber limitations). The movement of the transmitter antenna was 1.5 m at constant speed symmetric with respect to the AOAS. The result can be seen in figure 6.

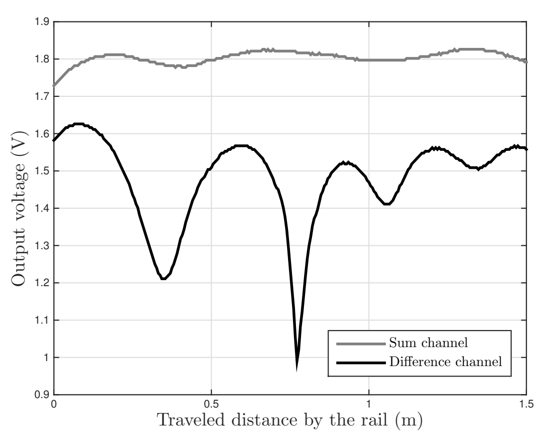

FIG. 6. Experimental result for a moving transmitter

C. Discussion

The theoretical simulation shows that, considering a fluctuation in the dynamic range of the detector of 10 dBm and, therefore, taking -85 dBm as lower limit the maximum reachable distance with the desired angular error is beyond 200 m, which means that without interference, the system should be able to detect the plane.

The results in the measures show that the noise level is below the logarithmic sensor's dynamic range, but some spurious and interference signals go over this level and affect the measures. More precisely, the noise level is around -174 dBm/Hz and, for a bandwidth of 10 MHz added to the noise due to the own system devices and the amplification, it is safe to assume that the noise level is at -85 dBm, which matches the suppositions in which the theoretical simulations where based. Nonetheless, when leaving the lab, the number of interferences increases and better filtering is required to perform reliable measures.

As can be seen in figure 6. in the measure with the antenna in the rail simulating a plane flying by, regardless the smooth and expected shape of the antennas' sum and difference diagrams, there appear some unexpexted side lobes on the difference channel and some undulations on the sum channel. One possible hypothesis is the non-ideal performance of the anechoic chamber where metallic objects were deployed (linear rail, tables, power supply, synthesizers, etc) and may had lead to multipath phenomena, originating these disturbances. Nevertheless, the main gap is present and unique, with the greatest positive value. Hence, the detection is possible.

V. CONCLUSIONS

After defining a problem and a possible solution, an intensive characterization of the case has been performed to show that such problem can be solved with the proposed method. It has been proven that radio-controlled slope soaring airplanes can be detected going through gates using an angle of arrival detection system. With the proper implementation, almost any desired specifications can be achieved to have a fast system with a very small angular error.

Nevertheless, during the process of construction of the prototype, there are some problems that have been detected. In order to make a functional device to be commercialized there are some improvements that need to be implemented to solve these mentioned issues and improve the relation with the user.

As mentioned in the results discussion section, the system needs better filtering in order to be able to work in open field. This can be achieved by using a superheterodyne receiver that allows narrower filtering and would drastically reduce the effect of the external and internal interferences.

Another improvement is the implementation of more directive antennas such as mircrostrip patch antennas that have a ground plane behind them that behaves better than the metallic mesh used.

Of course, these considerations need to be tested and quantified.

In order to make the system more efficient and user-friendly ideas of using a Raspberry Pi to connect the two needed detection systems via Wi-Fi to a central computer with an own interface to display the resulting times could be considered.

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