FIRE-CONTROL RADAR MODEL LABORATORY WORK

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ABSTRACT

Electrical engineering teaching is not an easy task because of the broad spectrum of knowledge to call for (electromagnetic, electronic, control, signal processing), each one having its specific formalism. To connect these different courses through a real-life application, we have decided to design a fire-control model based on a low-cost sonar system. This experiment has been designed for graduated students and is exploited in laboratory projects. Besides the playful aspects brought by the model, the project allows to face-off a real system and requires strong initiative from the students to success.

***Index Terms*—** Laboratory, experiment, radar, sonar, ultrasound, fire-control, Matlab, electrical engineering

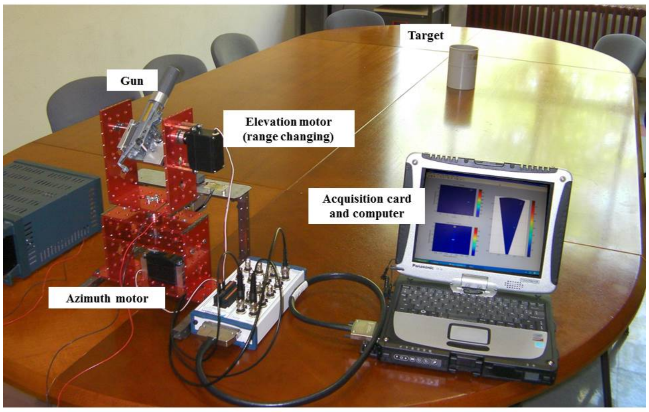

Fig. 1. Model overview

1. INTRODUCTION

In everyday life we encounter systems based on the measurement of a wave propagation delay. Global Positioning System (GPS), Medical ultrasonography, aeronautical radionavigation systems, automotive park assist systems are some examples based on this principle, to cite a few. Radar system is another field of application that allows to detect passives targets, estimate their range and speed and possibly track them along their trajectory. The scope of radar systems is wide [1] [2]. From airborne or spaceborne detection and imaging devices to air-traffic management or meteorological forecasting, both for military or civilian applications.

Therefore, teaching such a system is an important issue for aeronautical engineers. The main difficulty associated with these technical courses lies in the wide-ranging fields of the theoretical knowledge needed to tackle this subject. Indeed, one needs solid background about electromagnetic waves propagation, micro-waves, electronics, signal processing, real-time systems and control in order to perfectly understand a radar system. All these subjects have been addressed in specific courses, but the delay and the notation differences between them can be a real difficulty for students.

Thus, in order to open up all these courses, we have decided to create different laboratory models of real life radar systems. These experiments are simplified models compared to real ones because of our academical goal, but they remain very close to reality. They allow to show through real-life applications how the students can use in practice the skills gained in theoretical courses. Moreover, these models put the fun back into laboratory working. Like this, we have developed, for instance a Synthetic Aperture Radar (SAR) system to illustrate active airborne or spaceborne imaging devices [3] [4]. Such experiments are also described in [5] [6].

In this paper, we present a new radar system aimed to fire a moving target. This kind of systems are commonly called Fire-Control Radar (FCR) [7]. The model is composed of two subsystems (see fig. 1):

- *the measurement module*, based on an active aerial sonar aimed to detect a moving target, estimate its range and bearing. This subsystem is based on one wide-bandwidth ultrasonic transmitter and two receivers.
- *The gun turret position and fire control*, composed of a gun aimed to launch steel marbles up to a ten meters and two positioning motors to steer the gun.

The whole system is directly controlled from a computer using Matlab® and a National Instruments® acquisition card (NiDaq 6064E).

The paper is organized as follows. Section 2 presents a more detailed overview of the whole system and explains the project organisation. Then, the main signal processing concepts tackled during this laboratory work are described in sec-

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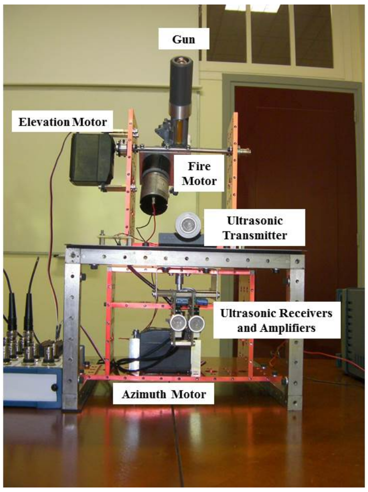

Fig. 2. Model close-up

tion 3. Section 4 concludes this paper and gives some feedbacks.

2. SYSTEM DETAILED DESCRIPTION AND STUDENT OBJECTIVES

2.1. The Sonar subsystem

As its name says, a real-life FCR is designed with an electromagnetic waves transmitter and receiver. In our experiment, the maximum ranging is not a strong constrain so that it is much more simple to use ultrasound waves. Thereby, the frequencies to be used to achieve short wavelength and a good ranging resolution is much lower. This transposition from the electromagnetic to sound allows to use low-frequency amplifiers, standard acquisition cards and the amount of sampled data to be processed is small. The only difference is the impossibility of polarimetric processing, but it is out of the scope of this project.
The hardware of the sonar is composed of three $400WB16$ Prowave® ultrasonic wide-bandwidth transducers and narrow bandwidth amplifiers (see fig. 2). The central frequency of the system is approximately $f_0 = 40\,KHz$ and the bandwidth can reach $10\,KHz$. The amplifiers are designed to reduce the thermal and environmental noise and supply a $[-5, 5]$ voltage to the acquisition card. This part is given to the students. We use a two sensors array receiver antenna to estimate the Direction of Arrival (DoA) of the wavefront. The waveform to be transmitted is directly designed and sent from Matlab. This way, the students have a total freedom on its design.

2.2. The gun turret position and fire control

This subsystem is composed of three actuators. Two servomotors control the pointing angles to reach the target using a marble launched by a spring compressed by a third motor. This motors are all controlled from Matlab through specific amplifiers. This part is also given to the students. It has to be noticed that the fire-system is designed to give a constant velocity to the marble. Hence the fire distance has to be controlled thanks to the elevation motor by calculating the range of the ballistic trajectory.

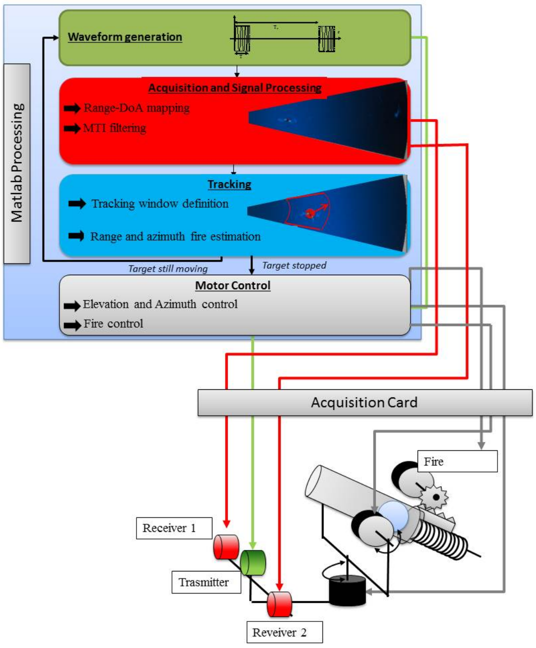

Fig. 3. tasks to be conducted

2.3. Objectives given to the students and project organization

This project has been design for graduate students, having strong background in all electrical engineering fields (electronics, control, computer science, signal processing). They are also familiar with Matlab programming. They work in groups of 4 students during 20 hours, half of this duration is supervised. The main goal given to the students is to try to throw the marble inside a 15-cm diameter pot. This target can be moved using a radio controller. The target is supposed to be the only moving element so that it can be easily extracted from the ground clutter. Figure 3 allows to clarify the different tasks to be conducted.

The project is split in 4 milestones :

- a specific teaching about radar signal processing during 2 hours (see part 3),
- software design and programming tasks during 14 hours,
- tests and performance measurements during 4 hours,

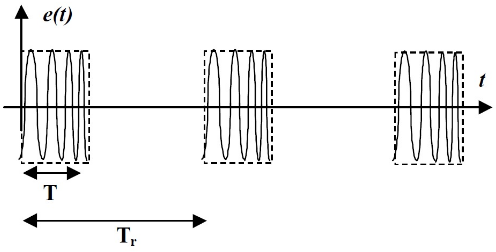

Fig. 4. standard radar waveform

- writing report of their work,
- and an oral exam of 30 minutes for the whole group.

The final mark is a mean of this last oral exam as well as their report and the way followed to obtain their results.

3. MAIN SIGNAL PROCESSING TOPICS TACKLED IN THE PROJECT

In this part, we present the basics of the radar processing as they are introduced to the students during the first stage of their project.

Any radar or sonar system is based on the transmission of a specific wave design to detect and estimate the range, velocity and DoA of the targets. The classical waveform is composed of a repetition of pulses as represented on figure 4. Before being processed, the signals are first converted from real to their equivalent complex form using an Hilbert transform. Indeed, we do not transmit and receive both in-phase and quadrature components in this experiment. So, we have to re-construct them first.

3.1. Ranging

The main objective of a radar is to estimate the range of a target or equally the propagation delay, as the wave celerity is supposed fixed and known ($c = 340\,m/s$, for sound in the air at $\theta \simeq 20^oC$). In presence of additive white Gaussian noise, the optimum processing (also known as **matched filter**) reduces to a simple cross-correlation of the received signal with the known transmitted signal. If we use a non-modulated waveform, the correlation width depends on the pulse duration. Hence a compromise has to be done between the maximum ranging (that needs a high energy to be transmitted and consequently a long pulse duration) and the range resolution. To circumvent this drawback, we commonly use a linear-frequency-modulated wave. Thereby, it can be shown that the correlation width no more depends on the pulse duration, but on the spectral width of the signal, also called the bandwidth B. This so-called **pulse compression** technique allows to achieve a good range resolution ($\Delta d = \frac{c}{2B}$) while maintaining a long maximum ranging. Thereby, one can choose separately the pulse duration T and the bandwidth B depending on the ranging and resolution needed.

3.2. Speed measurement

If a target is moving, the instant propagation delay changes, leading to the so-called Doppler effect. It is straightforward to show that the frequency shift is $f_d \simeq -2\frac{v}{\lambda}$ where v is the radial velocity of the target and λ the wavelength. We usually consider that this frequency shift is small compared to the inverse of the pulse duration so that this frequency cannot be estimated from the data observed during a single pulse. The measurement method consists in observing this frequency from pulse to pulse. Hence, the choice of the Pulse Repetition Interval (PRI), T_r is crucial. Indeed, choosing a to long PRI leads to possible aliasing effects. But, in our case of interest, we don't need a complete non-ambiguous speed measurement of the target. We only need to reject all the non-moving objects to better detect our moving target. This clutter rejection based on the speed of the targets is called a **Moving Target Indicator** (MTI) filter.

Remark 1 *We can notice that it would have been difficult to choose an ad-hoc PRI if one wants to precisely measure the target speed. Indeed, as explained before, the maximum velocity that can be estimated without aliasing is* $v_{amb} = \frac{\lambda}{2T_r}$ *so that one needs a short* T_r *to limit undersampling. But choosing a short PRI imply a range ambiguity as one cannot differentiate between a delay* τ *and a delay* $(\tau + T_r)$*. Hence the maximum range that can be measured without ambiguity is* $d_{amb} = \frac{cT_r}{2}$*. We can observe that the product* $v_{amb}d_{amb} = \frac{c^2}{4f_0}$ *does not depend on the waveform parameters. In the case of ultrasound waves, this product is very little* $(0.72\,m^2/s)$ *so that it seems impossible to directly measure at the same time range and speed without any ambiguity. Besides, this conflicting behaviour between range and speed measurement leads to the existence of different operating modes in airborne radars, called High/Medium/Low Repetition Frequency (H/M/L RF).*

3.3. Joint range and velocity measurement

Given a burst composed of M pulses of N samples ($N = \frac{T_r}{T_s}$ where T_s is the sampling period), the common methodology to both measure distance and speed is to

- reshape the MN samples vector into a $M \times N$ matrix where each line corresponds to a period in between two pulses,
- apply the pulse compression to each line,
- apply a MTI filter to each column.

This last filter, operating from pulse to pulse is characterized by its Z-transfer function and its corresponding Bode diagram. The more basic one is $H(Z) = (1 - Z^{-1})$ and simply makes the difference between two different pulses. But

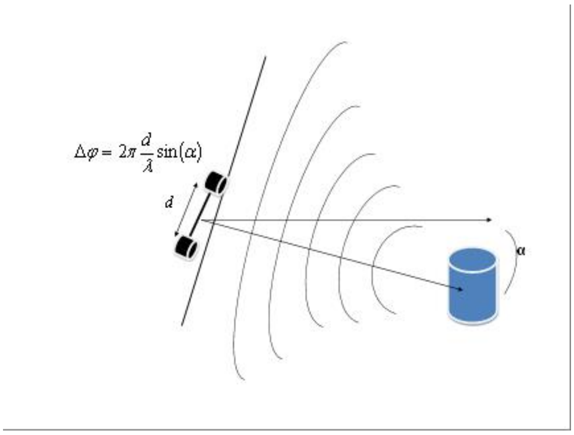

Fig. 5. Monopulse DoA estimation

the limited order of this Finite Impulse Response (FIR) filter leads to a reduced Doppler frequency bandwidth and, as a consequence, an amplitude loss for slow moving target. The students can design better FIR to improve moving targets detection.
This way the moving pot can be detected from the ground clutter. Its ranging can also be estimated and tracked while moving. When stopped, its last position can be stored to calculate the elevation angle needed to reach the target.

3.4. DoA measurement

Last, the azimuth of the targets with respect to the fire-system has to be measured. This estimation is performed thanks to the phase difference between the two receivers for each range after MTI filtering as presented on figure 5. This classical technique is called **phase monopulse** processing. Figure 6 shows an example of the output of this processing in case of a moving target in front of the fire-system at a $d = 1.25\,m.$ range.
The last step simply consists in moving the gun to the right angles. The gun turret has to move to the previously calculated azimuth and a specific elevation angle corresponding to the target range. This last angle can be estimated thanks to calibration mapping obtained through direct measurements or by inverting the well-known ballistic equations. In this last solution, the students have to estimate the marble speed when leaving the gun. This can be done using the ballistic equations and the range of the projectile within one try. Nevertheless, the elevation angle obtained using these theoretical equations has to be corrected to reach the target because of the air friction on the marble and other second order effects.

4. CONCLUSIONS

In this paper we have introduced a laboratory project based on a fire-control radar model. This system allows to better understand the complexity of a real-life radar system in a playful way. Moreover, this experiment allows to combine the different theoretical topics of electrical engineering, previously addressed separately. The project is conducted so that the students have to make choices on the waveform design and the processing to implement, in a practical environment. Obviously, this is the kind of challenge they will face in their future work as engineers.

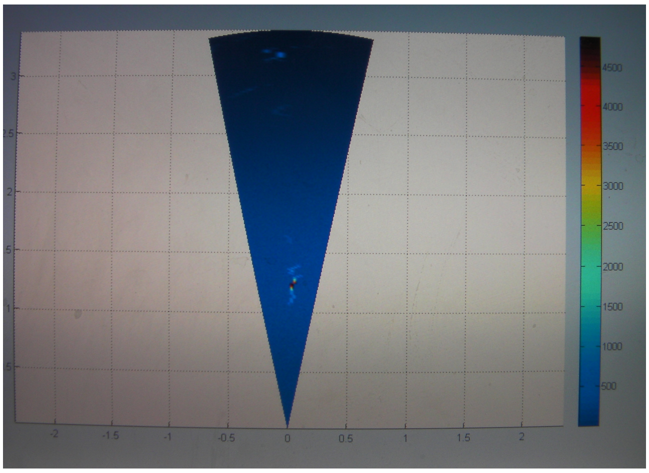

Fig. 6. Range-DoA Processing

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