Radar System for Cardiopulmonar Sensing Final report 2021-S2

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***Abstract*—In this paper, a project is presented to generate the detection and sensing of the heart rhythm and respiration rate of a human being. The RADAR applications focused on medical measure have an interesting background that was studied. From here a Cardiac and Pulmonary Rate Radar was developed, based on GNU Radio and an accurate signal processing using MATLAB. The main challenge was to meet the requirements described in the project proposal.**

***Index Terms*—Doppler radar, noncontact cardiopulmonary measurement, time-varying analysis.**

I. Introduction

The first usages of Radar on medical applications are from 1975 [4], when their value as a biology and medical tool was recognized. There was a huge number of investigations, seeking for non-invasive measurement methods for the patients and a better accessibility. Different investigators collaborated working on the use of RADAR spectrum in different bands (Ka, X, microwaves, etc...) and different approaches to processing the signals to get a reliable measure data, studing the modulation and demodulation, the use of filters and new algorithms. There are still challenges to face, related to get different variables and study the signals like the Quadrature. This background motivates to invastigate a realiable and accessible way to build a cardiac and respiratory rate RADAR.

The Radar system developed have a determiante specifications, related to the performance and operation:

TABLE I
Principal RADAR specifications

Operation Frequency	5.8 GHz
Measure distance	1 m
Cardiac Frequency Limits	72 to 84 bpm
Pulmonar Frequency Limits	approx 19 bpm

For the expermental validation of this RADAR, we use a testbed based on dynamic moves, but it does not consider the reflectivity and dielectric properties of the organs (heart and lunges).

Following, in the paper we first approach to the Antenna Elements, their desing and specifications in section II. Then, in section III, the transmitter, receiver and processing systems are described. The manufacturing process of the RADAR is revised in section IV. To validate the RADAR fuctionality, a testbed was built and its manufacturing is explained in section V. Finally, the experimental results, the Radar system validation and a general analysis is realized in section VII and VIII.

II. Antenna element

A. Helical antenna basics

In our design the chosen antenna type is a helical antenna. This is one of the antennas of the single-wire group and has the normal (perpendicular) and axial (beam) modes as main operation modes. Our interest in the use of the helical antenna is that the axial mode is useful in this design as long as it generates a radiation pattern in the direction of the helix axis. Another advantage of the axial mode is that the waves are nearly circularly polarized. This helical antenna has some advantages itself no matter its radiation mode. For example, these antennas have a simple design, highest directivity and a wider bandwidth. Nevertheless, it is important to be careful with the turns on the antenna since its efficiency decreases with the number of turns.

B. Helical antenna design

In order to design an antenna with a central frequency of 5.8 GHz, we used the information presented in the following figure, related with the helix geometry. In the figure are the helix and its associated dimensions as well as a triangle that allow us to determine the relation between the circumference, spacing, turn length and pitch angle of a helix.

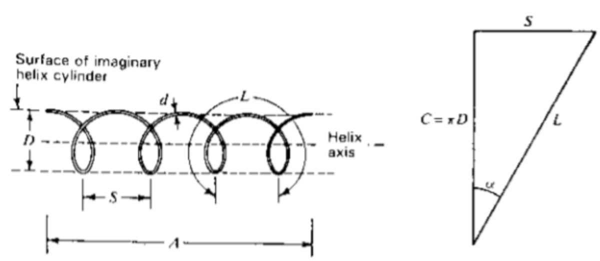

Fig. 1. Helix parameters and dimensions [3]

In the figure, it is possible to determine that the necessary parameters to properly design the antenna are the diameter of helix *D*, the circumference of the helix *C* that can be calculated as πD, the spacing between turns *S*, the pitch angle α that can be calculated as $\arctan\left(\frac{S}{\pi D}\right)$, the length of one turn *L*, the number of turns *n*, the axial length *A* that can be calculated as nS and the diameter of the helix conductor *d*.

For a frequency of 5.8 GHz, the resultant wavelength can be calculated using the following equation.

$$\lambda = \frac{c}{f} = \frac{3\times 10^8 \ \left[\frac{m}{s}\right]}{5.8\times 10^9 \ \left[\frac{1}{s}\right]} = 0.0517 \ [m] = 5,17 \ [cm] \quad (1)$$

There are some considerations that must be taken into account in the process of design of the antenna. Those considerations are shown below.

$$\frac{3}{4} \leq \frac{C}{\lambda} \leq \frac{4}{3} \tag{2}$$

$$S \approx \frac{\lambda}{4} \approx \frac{0.0517\ [m]}{4} = 12.925\ [mm] \tag{3}$$

$$12^\circ \leq \alpha \leq 16^\circ \tag{4}$$

The first step in the design is to solve the equation 2 to delimit the value of C and use this value to find other parameters, as shown below.

$$\frac{3\lambda}{4} \leq C \leq \frac{4\lambda}{3} \longrightarrow 3.877 \leq C\ [cm] \leq 6.893 \tag{5}$$

At this point, we chose a value of $C = 4.71\ [cm]$. With this value we can calculate the value of D as $D = \frac{C}{\pi} = \frac{4.71\ [cm]}{\pi} = 1.5\ [cm]$. Using this value of D, α can be calculated as,

$$\alpha = \arctan\left(\frac{12.925\ [mm]}{\pi 1.5\ [cm]}\right) = 15.337^\circ \tag{6}$$

Finally, the last two parameters of design are the number of turns and the ground plane. We chose the number of turns to be three, due that it was the value of n present in the design of the reference [1]. The ground plane is a metal plate with a height of 13.3 centimeters and a width of 11.2 centimeters. Finally, we chose 12-gauge copper wire as the material to build the antenna.

C. Simulation results

The original design of the antenna is part of an investigation of a group of students who tested this design in 2019. To complete the design of the antennas in this project, we base our design in the considerations present in [1]. In this article, the authors made the design in FreeCAD and then tested the characteristics of the antenna with MoMsim, a toolbox of MATLAB. The result of the simulations shown in [1] were good enough for our application, so we decided to use their design in our project. Nevertheless, when we built the antenna prototype, we made a frequencial analysis of the response of the antennas and found an optimal operation point at 5,87 GHz where the magnitude of the response of the antenna is -10,34 dB and the phase is 165,81°. The results of the analysis made are shown below.

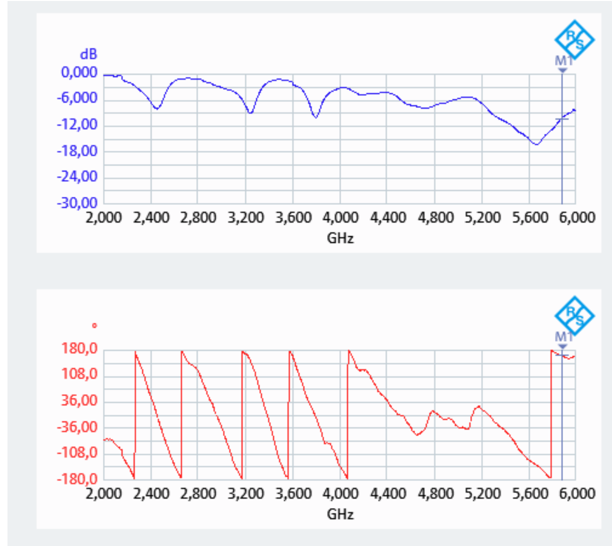

Fig. 2. Results of the frequency analysis for the manufactured antennas.

III. Transmitter and receiver, description and specifications:

The system developed was configured to operate at 5.8 GHz in the transmitter and receiver. The process to detect the heart and pulmonar rate is sending a cosine modulated signal at the operation frequency, the electromagnetic waves arrive to the target and are reflected. The received signal envolves the information about the target movement, working as a doppler RADAR. The system to modelate the transmitter signal and receive the echo is build using an USRP and the GNU Radio software. The USRP have the capability to work between 70 MHz and 6 GHz and with GNU Radio we configure a sample rate of 1 MHz. The bandwidth of the signal is 100 kHz, this is the frequency of the cosine envolved, but the frequencies of interest are below 4 Hz, where generally works the heart and lungs. Additionally, with GNU Radio is possible to configure the gain of the transmitter and receiver, which was configured at 41 and 53 respectively, looking to measure a target at a distance of 1 m.

IV. Processing algorithms

The processing of the signal pass by two principal steps: the first is an initial processing in the GNU Radio software where the signal is demodulated and pass through a first filter, and the second is a accurate frequency processing using matlab to clean the signal and get the correspond heart and pulmonary rate.

A. GNU Radio Processing

The initial processing is in the GNU Radio software where the signal is demodulated and pass through a first filter, where the frequency components are limited below 3 Hz, where are the frequencies of interest, following the complex signal is decomposed and the imaginary part is used as reference to detect the rates. Usign the GNU Radio tools, four graphics in real-time are generated: two about the frecuency component (before and after the first filter), the quadrature graph to apreciete the influence of the target movement on the complex signal and a real time response that register the movement received from the target. Finally the data is moved to a file that can be processed by MATLAB to get a more precise information about the rates.

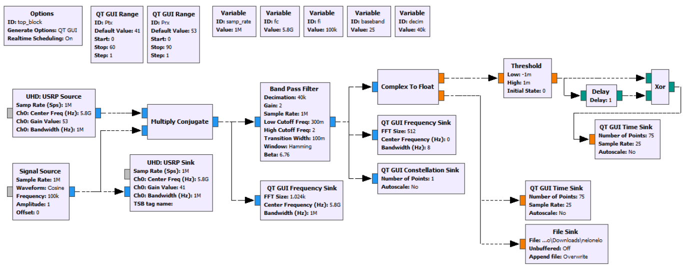

Fig. 3. GNU Radio blocks for Transmitter, Receiver and first processing

B. MATLAB Processing

The data obtained through GNU Radio and imported into MATLAB is passed through a low-pass filter, with a cutoff frequency of 3 Hz to remove unwanted frequency noise. Subsequently, two bandpass filters are used to separate the heart motion signal and the lung motion signal. The filter related to lung motion has cutoff frequencies of 0.1 mHz and 0.6 Hz, while the filter related to heart motion has cutoff frequencies of 0.6 Hz and 3 Hz. Finally, to extract the frequency of either of the two analyzed motions, we use the same procedure. We start by dividing the filtered wave with the envelope signal of the same, in order to keep the oscillatory component of the signal. Subsequently, the FFT is used to calculate the fundamental frequency of the oscillatory signal, which also corresponds to the cardiac or respiratory frequency, depending on the signal to which this procedure is performed. It is important to clarify that the filters used in this procedure are FIR filters, with an order of 50 in the case of the low-pass filter and an order of 200 in the case of the band-pass filters, and both use Hamming-type windows.

V. Prototype description

In the construction of the prototype, we used a cylindrical wooden stick with the diameter of interest as a reference on which we placed some reference points according to the parameters calculated in the section Antenna element. Then, we wind the copper wire following the references marked on the wooden stick to obtain the helicoidal antennas with the designed dimensions. Finally, we placed the antennas at a distance of 5 centimeters above the ground plane with the help of an insulating sheet, and then welded the SMA connectors to the antennas. Although our intention was to store the antennas in a radome, the height of the antennas did not allow us to place them in it, so to keep the antennas stabilized and immobile during the measurements, we decided to use an universal support. A picture of the final prototype is shown in the following figure.

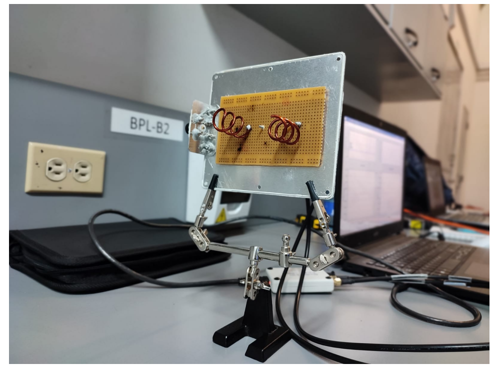

Fig. 4. Picture of the final prototype

VI. Validation testbed

Our testbed consists of a piece of metal mesh which has a height of 50 centimeters and a width of 45 centimeters. This mesh is attached to a wooden frame and slides over a piece of wood back and forth, approximately 10 centimeters. The shape of the displacement describes a sinusoidal function that represents the human breath, and this sine function has some impulses over it that represents the heart rate. The frequencies and amplitude of the sine function and the impulse function are different and independent of each other, in order to allow us to modelate different scenarios with the same algorithm. The movement is generated by a servo motor MG995 which is controlled by an Arduino MEGA. It is also important to note that the piece of wood where the frame is moving is wrapped in Contac in order to decrease the friction between the frame that holds the mesh and the base. Finally, the servo motor is attached to the frame through a series of sprockets that allows us to increase the velocity of the frame if it is greater than the maximum velocity of the motor, or increase the torque if necessary. Below are photographs of the validation testbed

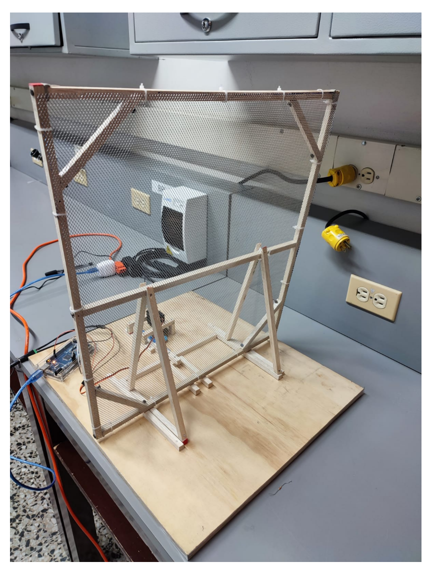

Fig. 5. Frontal view of the validation testbed

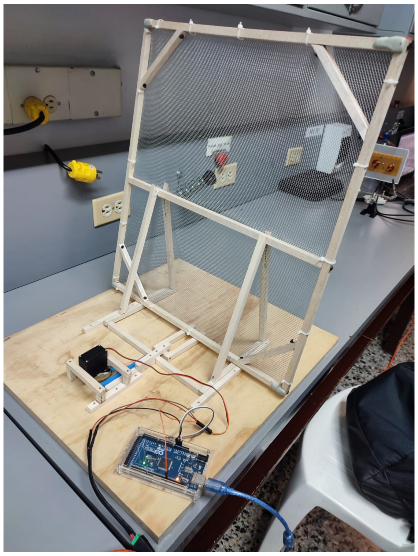

Fig. 6. Rear view of the validation testbed

VII. Experimental validation

For the experimental validation, a series of measurements was realized. The testbed is set to different cardiac and pulmonary frequencies and the system is tested, measuring the correspond rates. The radar register the real time measure with GNU Radio, after the data is computed in MATLAB to get the rates of interest. To validate the system different frequencies was evaluated. The most important parameter is keep the measure error below 20%, and this condition bound the operation of the system: for the heart rate, the operation is limited approximatly from 1.2 Hz to 1.4 Hz, which is equivalent from 72 to 84 bpm. The pulmonar rate is limited about 0.325 Hz, equivalent to 19 bpm. The next table shows the results within the operation limits and the correspond measurement error.

TABLE II
Experimental Results within the operation limits

Pulm. Freq. [Hz]	Cardiac Freq. [Hz]	Measured Pulm. [Hz]	Measured Cardiac [Hz]	Pulm. Measure error[%]	Cardiac Measure error[%]
0.350	1.40	0.3513	1.373	0.37	-1.93
0.350	1.30	0.4560	1.369	30.29	5.31
0.350	1.20	0.5510	1.372	57.43	14.33
0.325	1.40	0.4180	1.272	28.62	-9.14
0.325	1.30	0.3310	0.963	1.85	25.92
0.325	1.20	0.4210	1.265	29.54	5.42
0.300	1.40	0.4169	1.185	38.97	15.33
0.300	1.30	0.3063	1.472	2.10	13.22
0.300	1.20	0.5974	1.187	99.13	1.07

One of the measurements with the least errors obtained for the experimental validation was presented in dataset number 8. These results are presented below in the form of plots obtained by processing the detected signal using MATLAB.

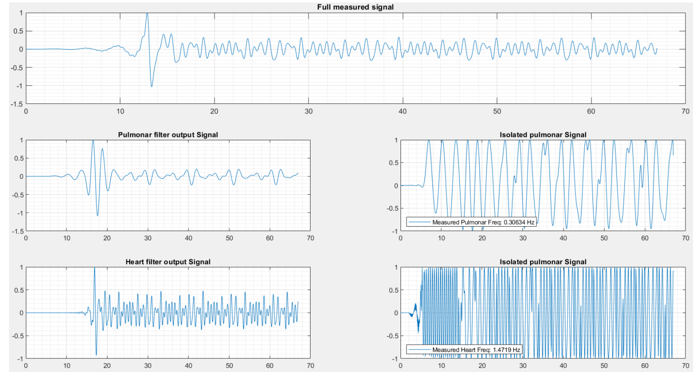

Fig. 7. Resultant signals of MATLAB processing for a testbed settings of 0.3 Hz as pulmonar frequency and 1.3 Hz as heart rate frequency

With these results, it is necessary to clarify that the testbed was designed to simulate the dynamic characteristics of the thorax, so that the movements performed by the testbed are similar to the movements of interest, although the simulated movements present a larger magnitude than the natural one. In addition, some dielectric characteristics of human organs were omitted, since the priority was to ensure correct motion detection, rather than to strictly model all the characteristics of a human thorax.

VIII. Analysis of results

With respect to the results obtained, it is possible to determine that all the heart rate measurements comply with the requirements by presenting an error of less than 20%. However, when analyzing the results obtained for the respiratory rate, only two of the measurements complied with the requirements, since all the others presented an error that was too high. Although some systems were implemented to try to reduce the error in these measurements, the fact of having an operating frequency close to 0 Hz makes controlling the error a complicated task to accomplish with the tools at hand.

In the *Experimental validation* section, it is possible to determine that the heart movement is detected and processed way better than the lungs movement. For this reason, the next step in the development of a device as the proposed in this paper is to strengthen the detection of signals with low frequency or look for some other methods that allow to reduce the error when the frequency of operation is near to zero.

In accordance with the country's regulations regarding the use of the spectrum, this project is located within an ISM band, intended for Industrial, Scientific and Medical use. It is important to take into account that in case of leaving aside the validation of the project through the testbed and testing the prototype on human beings, the maximum values of exposure to electric and magnetic fields, consigned in the RETIE, must be taken into account. [2]

NOTES

The GNU Radio, MATLAB and Arduino scripts used to create this project and the dataset of the experimental validation can be consulted in this GitHub repository:

https://github.com/ssuarezs/RadarProyect2022

REFERENCES

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