RHL-RADAR Remote Laboratory

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Abstract. An Educational Remote Laboratory is a software and hardware solution that enables students to access real equipment from any location. In the literature there is a wide range of remote laboratories in many fields (e.g., robotics, electronics, physics, chemistry). However, few experiences have been developed for educational Radar purposes. Radar, which stands for "Radio Detection and Ranging," is a technology that utilizes radio waves to detect distant objects to measure physical parameters like the range, angle, or velocity. Most Radar systems are composed of a transmitter, receiver, antennas and a computer to apply signal processing methods of estimation. This paper introduces the Radar remote laboratory developed by the Remote Hub Lab (RHL). The laboratory involves the creation of a remotely controllable Radar system prototype designed to estimate the rotational velocity of a fixed structure, with initial results presented. This educational tool is oriented toward undergraduate and graduate engineering students, offering them a remote platform to supplement their Radar courses by actively engaging in real-world Radar problem-solving exercises.

Keywords: GNU Radio, Software Defined Radio, remote laboratory, embedded systems, Radar

1 Introduction

Remote laboratories in engineering education curricula have become increasingly popular due to their low cost, 24/7 availability, and the absence of geographic proximity restrictions [1, 2]. This educational approach not only fosters collaboration among peers but also significantly improves accessibility for students with disabilities [3]. Within the electrical engineering department, an extensive array of remote labs has been introduced as a valuable alternative to traditional labs, providing students with hands-on experimentation opportunities to complement theoretical knowledge [4, 5]. One notable advantage of remote labs in electrical engineering is that parameters like electrical current and electromagnetic waves are not visible or audible, eliminating the need for sound or video transmission [6]. In the case of electromagnetic waves, which play an important role due to the propagation of electromagnetic energy in the radio frequency (RF) spectrum is fundamental to designing and implementing effective wireless communication systems.

In this context, the RHL[1] group [7] and LabsLand[2] initiated the development of Remote Engineering laboratory for Inclusive Access (RHL-RELIA), a remote laboratory for wireless communication utilizing Software Defined Radio (SDR) devices. This laboratory offers the advantage of a low-cost and open-source philosophy, allowing students to access it through a web browser, thereby avoiding the expenses associated with specialized software licenses [7,8]. RELIA was developed as a implementation of MELODY, a model tailored explicitly for SDR remote labs. MELODY is characterized by its technology-agnostic and open-source approach [9].

Following with the idea of developing remote educational tools based on the MELODY model, RHL group worked on the development of a RHL-RADAR remote laboratory with the idea of offering it in Radar classes where students can manipulate remotely a radar system to experiment and apply Radar configuration and signal processing techniques. Typically in the traditional Radar courses, students apply signal processing techniques in the plane of simulation and they might build a hands-on project. However, these activities often demand a significant background in in electrical engineering and electromagnetic to build and install a Radar system. With a remote laboratory students have the Radar system installed and focus mostly in the experiment's configuration and the Radar signal processing which is beneficial from the cost-time development which is essential in classes and it can motivate students from other specialities to take Radar classes since they don't to have to handle with other backgrounds required.

This paper introduces RHL-RADAR, which implements a Continuous Wave (CW) Radar application capable of estimating the rotational velocity of a fixed structure. The obtained results are subsequently compared with those from a tachometer used for measuring rotational speed. The structure of the article is as follows: Section 2 offers a review of Radar tools in the education field. Section 3 provides an overview of the CW Doppler Radar, offering a mathematical analysis that elucidates the micro-Doppler effect generated by rotating structures. It also incorporates technical details about the antennas and digital receiver employed in the experiment. Section 4 presents and discusses the outcomes derived from the CW Radar, drawing comparisons with measurements obtained from the tachometer. Finally, Section 5 summarizes the primary findings of the article and outlines the conclusions and future work derived from the study.

2 Background

In a remote laboratory, students can remotely access actual equipment situated in the university, setting it apart from virtual laboratories that typically involve simulations rather than tangible equipment [5]. The composition of a remote laboratory includes both software and hardware elements, and owing to the

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[2] https://labsland.com

advancements in internet technology, it now allows for the execution of intricate experiments closely mirroring traditional learning experiences [10, 11].

While the literature encompasses a diverse array of remote laboratories across various fields, such as robotics, electronics, physics, and chemistry [12], there is a notable scarcity of experiences specifically designed for Radar applications. A Radar system utilizes radio waves to detect, locate, track, and identify objects, finding widespread applications in military, aviation, meteorology, navigation, and traffic control [13]. In the educational context, students pursuing electrical engineering often enroll in Radar classes, typically as elective courses or at the graduate level.

One compelling Radar project is offered by the University of Oklahoma (OU), presenting an integrated interdisciplinary approach to prepare students in meteorology Radar, facilitating the acquisition of quantitative weather data. OU's initiative features a laboratory with hands-on hardware setups and signal processing, complementing an extensive Radar curriculum spanning 10 courses [14]. Despite containing multiple Radar systems, this laboratory requires the physical presence of students for full operation.

Another intriguing Radar project is developed by the Massachusetts Institute of Technology (MIT) Lincoln Laboratory, where a low-cost Radar system has been designed for students participating in a Massive Open Online Course (MOOC). Valued at $530, the system is available for online ordering, guiding students through the collection and processing steps to record their own data. This project's distinctive feature lies in its emphasis on allowing students to work with and interpret real-world data, a significant departure from standard sample files [15]. This useful tool requires that a student buy and build their own Radar system and test the results at home while is taking an online class.

The objective of the RHL-RADAR project is to develop a new Software Defined Radio (SDR) remote laboratory featuring a specialized peripheral—a fan designed for testing Radar applications [16]. While RHL-RADAR is currently in the development phase, its characteristics align well with explaining the MELODY model in this context. This alignment is crucial for evaluating MELODY using a prospective remote laboratory. RHL-RADAR aims to provide students with the convenience of conducting experiments from a distance, eliminating the need for direct manipulation of physical hardware or manual configuration of Radar parameters.

3 System Design

3.1 Continuous Wave Radar

Continuous Wave (CW) Radar transmits a continuous radio frequency signal at a fix frequency without any interruption. This type of Radar is able to estimate the velocity of a target by measuring a portion of the signal reflected back to the Radar receiver. The receiver then analyzes the frequency shift, known as the Doppler shift, between the emitted signal and the received signal.

CW Radar is typically used in applications such as speed detection, however, CW Radar can't estimate range resolution because it does not utilize pulse timing to measure distances.

One application of continuous wave (CW) Radar is to estimate the rotational velocity of objects. In this particular application, the frequency of the reflected signal received by the Radar undergoes modulation, resulting in an effect known as micro-Doppler. The CW Radar system designed for this purpose is illustrated in Figure 1.

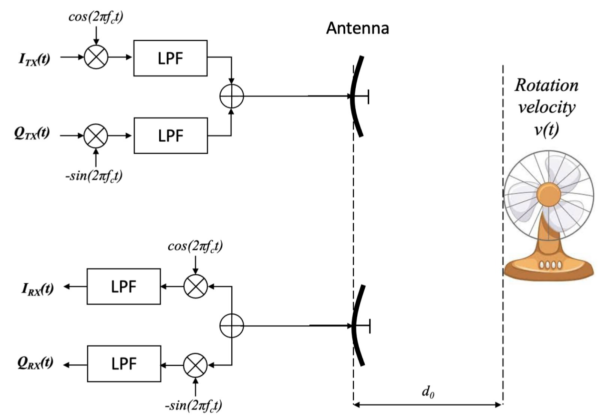


Fig. 1: CW Doppler Radar experiment diagram.

3.2 Modeling of The Rotating Structure

The mathematical analysis of the received signal in Doppler Radars encountering a rotating structure with blade length L involves complex modeling due to the requirement of azimuth and pitch angles of the incident wave. However, in the case of a fixed rotating structure where the Radar is aligned with the center, the analysis can be simplified. In this scenario, at time $t = 0$, a scattering point P_0 positioned at an initial rotation angle ϕ_0 begins rotating counterclockwise with an angular velocity of Ω. The movement is depicted in Figure 2.

At a given time t, the point P undergoes rotation and is denoted as $P(t)$, with the rotation angle represented as $\phi_t = \Omega t + \phi_0$. The distance from the Radar to the point P can be expressed as:

$$R_p(t) = \sqrt{(R_0 + x_t)^2 + y_t^2} \tag{1}$$

$$R_p(t) = \sqrt{(R_0 + L\cos\phi_t)^2 + (L\sin\phi_t)^2} \tag{2}$$

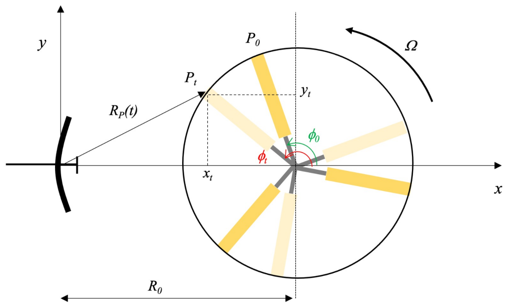


Fig. 2: Rotating structure diagram.

$$R_p(t) = \sqrt{R_0^2 + L^2 + 2R_0 L \cos(\phi_t)} \tag{3}$$

$$R_p(t) = \sqrt{R_0^2 + L^2 + 2R_0 L \cos(\Omega t + \phi_0)} \tag{4}$$

In the far field distance can be reduced to:

$$R_p(t) = R_0 + L \cos(\Omega t + \phi_0) \tag{5}$$

According to the Radar theory, the echo of a scattering is attenuated and delayed. The is delayed is represented by:

$$\tau(t) = \frac{2d_0}{c} + \frac{2v(t)}{c} \tag{6}$$

where d_0 is the distance between the Radar and the target and $v(t)$ is the velocity of the target. However, because it is a static infrastructure then $v(t)$ is 0. Therefore for this specific case the echo returned is:

$$s(t) = A_r \exp\{-j2\pi f_{TX}(t - \tau(t))\} \tag{7}$$

Where A_r is the amplitude of the received signal and f_{TX} is the frequency of transmission. Replacing

$$s(t) = A_r \exp\{-j2\pi f_{TX}(t - \frac{2R_p(t)}{c})\} \tag{8}$$

$$s(t) = A_r \exp\{-j2\pi f_{TX} t + j\frac{4\pi R_p(t)}{\lambda}\} \tag{9}$$

$$s(t) = A_r \exp\{-j2\pi f_{TX} t + j\frac{4\pi[R_0 + L\cos(\Omega t + \phi_0)]}{\lambda}\} \tag{10}$$

Thus, the base-band signal at the scattering point P_t is:

$$s_p(t) = A_r \exp\{j\frac{4\pi R_0}{\lambda}\}\exp\{j\frac{4\pi L\cos(\Omega t+\phi_0)}{\lambda}\} \quad (11)$$

For a fan with N blades, the initial rotational angle of each blade is:

$$\phi_k = \phi_0 + \frac{2k\pi}{N} \qquad k = 0, 1, \ldots, N-1 \quad (12)$$

The expression for the phase function of the echo at the tip of the blade k is as follows:

$$\phi_k(t) = \frac{4\pi L}{\lambda}\cos(\Omega t + \phi_0 + \frac{2\pi k}{N}) \quad (13)$$

As it is know the frequency features of the blade are represented by the Doppler frequency shift is the derivative of the phase:

$$f_{D,k}(t) = \frac{1}{2\pi}\frac{d\phi_k(t)}{dt} \quad (14)$$

Then resolving equation 14 taking from equation 13

$$f_{D,k}(t) = -\frac{2\Omega L}{\lambda}\sin(\Omega t + \phi_0 + \frac{2\pi k}{N}) \quad (15)$$

From Equation it can be deducted that the rotational speed modulates the instantaneous Doppler frequency as a sinusoidal curve [17]. Therefore, the maximum Doppler is when

$$f_{Dmax} = \frac{2\Omega L}{\lambda} = \frac{2v}{\lambda} \quad (16)$$

Figure 3 illustrates the simulation of micro-Doppler characteristics for rotating 5 blades at a speed of 900 RPM, which simulates real maximum velocity $v3$ of the fan.

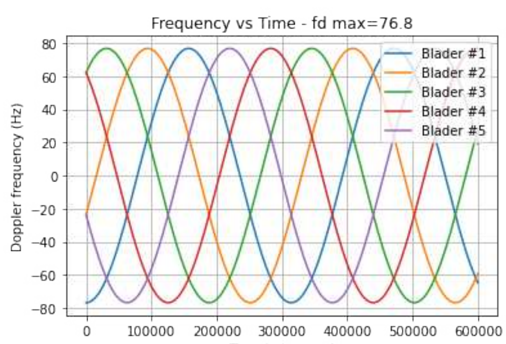


Fig. 3: The micro-Doppler features of a fan with 5 blades.

The radial velocity (v_r) of a target can be determined by measuring the frequency shift (fd) [13]. This provides information about the target and its components. Hence, estimating the RPM (rotations per minute) of a rotating structure, like rotating blades, can be achieved by observing the micro-Doppler effect generated by the rotational motion. The relationship between the observed frequency shift and the RPM of the rotating structure can be expressed as:

$$f_d = \frac{RPM_{fan} \times N}{60} \tag{17}$$

where f_d is the frequency shift and N is the number of blades of the fan.

3.3 Antenna

In Radar applications, it is essential to use an antenna that emits radio waves predominantly in a specific direction, allowing for concentrated transmission of energy in that particular direction. For this experiment, a Log Periodic Antenna is chosen because it exhibits a directional radiation pattern, offers high gain ($9 - 10dBi$), and is capable of operating across a wide range of frequencies. The specific antennas employed are the HG72710LP-NF models from L-com, which have a frequency range of $698 - 960$ MHz and $1710 - 2500$ MHz. These antennas feature a horizontal beam width of 78 degrees and a vertical beam width of 56 degrees. Additional specifications can be found in [18].

3.4 Digital Receiver

The ADALM-Pluto from Analog Devices [19] is a digital receiver that offers a wide range of features and capabilities that make it suitable for Radar signal processing. Its frequency range, high dynamic range and capability of working in full-dupplex and its programmable nature allows for flexible configuration and adaptation to various Radar scenarios.

Furthermore, the inclusion of ADALM Pluto in the GNU-Radio Companion (GRC) software libraries simplifies the utilization of its powerful processing capabilities [20]. With its USB 2.0 data transfer capability, it becomes an affordable device that can be employed in conjunction with low-cost embedded systems like Raspberry Pi. These characteristics collectively make ADALM Pluto an attractive choice for Radar applications, particularly in educational settings.

4 Results

Figure 4 illustrates the Radar prototype system. The experiments utilized a fan as the target object with three distinct velocities: v1, v2, and v3. In this context, v1 represents the lowest velocity, v2 corresponds to the middle, and v3 signifies the maximum velocity. To enhance reflectivity, the blades of the fan were coated with aluminum. Additionally, the configuration parameters detailed in Table 1.

One crucial benefit of SDR technology is the ability to perform the mixing process for signal conversion to baseband digitally. Additionally, the conjugate multiplication can be carried out during data acquisition, providing a significant advantage over its analog counterpart. Consequently, this expedites the development time of RF prototypes.

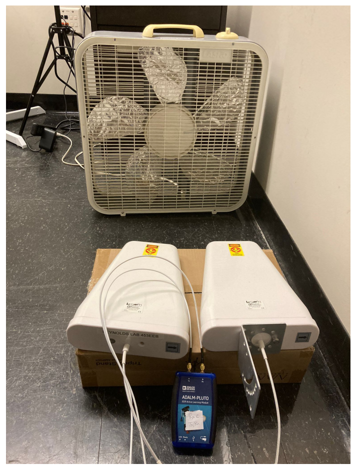


Fig. 4: CW Radar system installed.

Table 1: CW Radar Configuration.

Parameter	Value
Frequency	2.4GHz
Tx Gain	0dB
Rx Gain	60dB
Sample Rate	2MHz
Data Type and Resolution	I/Q 64bits
Low Pass Filter cut-off frequency	500 Hz

The outcomes derived from the Radar experiment are depicted in Figure 5, showcasing a spectrogram. A spectrogram visually represents the spectrum of frequencies in a sound or signal, illustrating how they change over time [21].

Initially, the velocities may not be clearly visible in the Spectrogram. However, after applying a low-pass rectangular window filter, the Spectrogram in Figure 6 reveals three distinct velocities: $v3$, $v2$, and $v1$. The corresponding spectra and RPM measurements for these velocities are presented in Figures 7, 8, and 9, respectively.

By extracting a specific time slice from the data, it becomes possible to obtain a more precise estimate of the Doppler frequency, which can then be compared with the measurements obtained from the tachometer. The comparison between

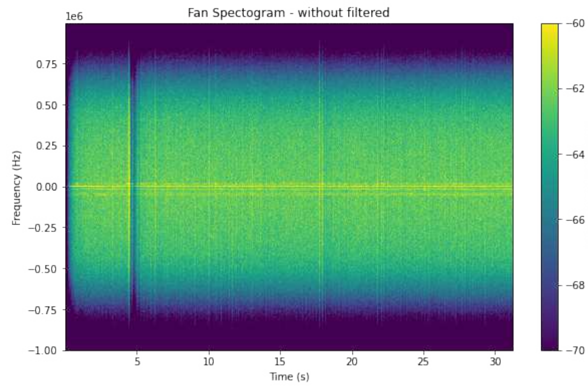


Fig. 5: Raw data Spectrogram of the rotating structure experiment.

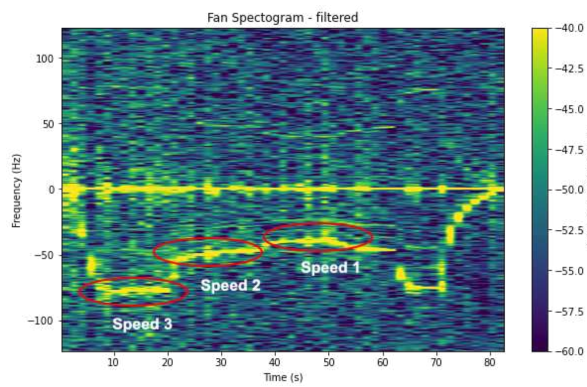


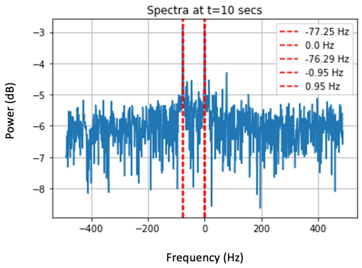
Fig. 6: Filtered data Spectrogram of the rotating structure experiment.

the two values can be performed using Equation 17, allowing for a quantitative assessment of their agreement.

The results demonstrate a strong correlation between the two measurements, as indicated by the low error values ranging between 1-3%. Table 2 provides a summary of the three measurements obtained.

Table 2: Comparison of results from Radar and Tachometer's measurement.

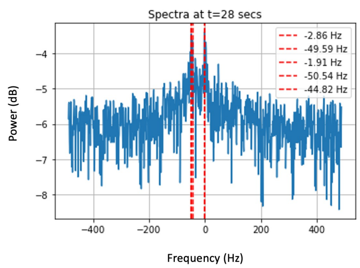
Tachometer (RPM)	Radar (Hz)	Error (%)	Std Dev	Power (dB/Hz)
900.4 (v3)	76.29 - 77.25	1.57 - 2.92	4.92	-3dB
611.5 (v2)	49.59 - 50.54	0.74 - 2.68	3.88	-3dB
530.8 (v1)	44.18 - 45.57	0.94 - 3.08	3.44	-3dB



(a) Spectrum of the fan - v3.

(b) RPM of Fan's speed - v3.

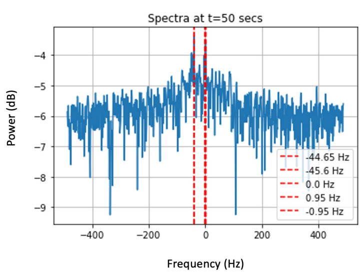
Fig. 7: Spectra and tachometer's measurement of velocity - v3.



(a) Spectrum of the fan - v2.

(b) RPM of Fan's speed - v2.

Fig. 8: Spectra and tachometer's measurement of velocity - v2.



(a) Spectrum of the fan - v1.

(b) RPM of Fan's speed - v1.

Fig. 9: Spectra and tachometer's measurement of velocity - v1.

5 Conclusions and Future Work

In summary, this article introduces a prototype of a Remote Laboratory dedicated to Radar experiments, featuring a configurable Continuous Wave (CW) Radar system.

The results reveal a significant correlation between Radar and tachometer measurements, with a margin of error ranging between 1-3%, signifying a reasonably accurate estimation.

The use of affordable components, such as the Adalm Pluto (priced at $230) and Raspberry Pi 4B (priced at $120), enhances the accessibility and value of Radar experiments in Engineering Education.

The integration of this prototype into a remote SDR laboratory empowers students to conduct Radar experiments from any location, thereby augmenting the flexibility and accessibility of the learning process.

Moreover, there exists potential for expanding the scope of Radar experiments, including the exploration of CW Radar for Multi-Target estimation or the investigation of Frequency-Modulated Continuous Wave (FMCW) Radar for estimating both range and Doppler parameters.

As part of future plans, this remote laboratory can be implemented in an ultra-concurrent mode, a type of remote laboratory allowing students to interact with pre-recorded real data. This mode proves advantageous when facing infrastructure challenges, making it impractical to provide a dedicated remote laboratory station for each student.

Acknowledgements

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