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Radar Based Systems Design and Optimization for Biomedical Applications

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Biyomedikal Uygulamalar için Radar Tabanlı Sistem Tasarımı ve Optimizasyonu

Şahin YILDIZ, M. Bahaddin KURT

Dicle University, Electrical and Electronics Engineering Department, Diyarbakır, Türkiye

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Abstract

Radar-based applications have great importance in interpreting moving objects. In this study, it is aimed to develop a radar system for biomedical applications. The radar system is created by combining various components. These components consist of antenna, modulator, microwave and low-pass filter circuit. Antennas are important components of the radar system. Antennas have been optimized with geometric changes. The operating frequency of the antennas was improved and increased from 2.36 GHz to 2.40 GHz. The initial value of the antenna gain was 3.02 dB, which was increased to 3.67 dB for improvements. The initial value of return loss was -19 dB, and with the work done, it was increased to -28 dB. An analog-digital converter is used in the radar system for traceability of the signal reflected from the target. An object moving forward and backward was placed in front of the system and the signals reflected back from the target were monitored. It was observed that the signal amplitude was between 3 and 3.4 during the time-period when the target object was far away from the system. In close-range measurement, it was observed that the signal amplitude was between 2.8 and 3.8. It was concluded that these movements can be interpreted in biomedical applications with signal processing techniques.

Keywords: *Radar antenna, Biomedical applications, Optimization.*

Öz

Radar tabanlı uygulamalar, hareketli nesneleri yorumlamada büyük öneme sahiptir. Bu çalışmada biyomedikal uygulamalara yönelik bir radar sisteminin geliştirilmesi amaçlanmaktadır. Radar sistemi çeşitli bileşenlerin bir araya getirilmesiyle oluşturulur. Bu bileşenler anten, modülatör, mikrodalga ve alçak geçiren filtre devresinden oluşur. Antenler radar sisteminin önemli bileşenleridir. Antenler geometrik değişikliklerle optimize edildi. Antenlerin çalışma frekansı iyileştirilerek 2,36 GHz'den 2,40 GHz'e çıkarıldı. Anten kazancının ilk değeri 3,02 dB olup iyileştirilerek 3,67 dB değerine çıkarıldı. Geri dönüş kaybı ilk değeri -19 dB olup, yapılan çalışmalarla -28 dB değerine çıkarıldı. Hedeften yansıyan sinyalin izlenebilirliği için radar sisteminde analog-sayısal dönüştürücü kullanılmaktadır. Sisteminin önüne ileri ve geri yönde hareket eden bir cisim yerleştirilerek hedeften geri yansıyan sinyaller izlendi. Hedef nesnenin sistemden uzakta olduğu zaman diliminde sinyal genliğinin 3 ile 3,4 arasında olduğu gözlendi. Yakın mesafe ölçümde sinyal genliğinin 2,8 ile 3,8 arasında olduğu görüldü. Bu hareketlerin biyomedikal uygulamalarda sinyal işleme teknikleriyle yorumlanabileceği sonucuna varılmıştır.

Anahtar Kelimeler: *Radar anten, Biyomedikal uygulamalar, Optimizasyon.*

1. Introduction

Radar-based applications are used in many fields such as military, meteorology, traffic and various health applications. Radar, originally short for 'Radio Detection and Ranging', has a rich history based on the classical experiments of Heinrich Hertz in the 1880s (Skolnik., 2002). The working principle of radar-based applications used for speed and frequency detection is based on the doppler phenomenon. Doppler frequency detection is used in various applications today. For example, artificial aperture radar (AAR) imaging with Doppler-based tomographic methods (Mensa et al., 1983), direction detection of multiple targets with tracking radar (Lin et al., 2007), traffic radars and many other applications require Doppler frequency detection. These require that the usage needs be well defined, and the characteristics of the radar systems are well known. As can be understood from their areas of use, Doppler radar systems have provided great benefits in many areas from past to present. Radar systems are an important factor facilitating adaptation to changing healthcare needs. Radar systems are analyzed in terms of block diagrams and behavioral equations. These systems are kept on the agenda of research and development studies intensively in tumor detection, vital signs monitoring and medical imaging systems in the field of medicine.

Researchers have demonstrated the feasibility of radar-based sensing systems for detecting or monitoring human

*Sorumlu Yazar/Corresponding Author: Şahin YILDIZ e-posta/e-mail: sahinyildiz@dicle.edu.tr

respiratory rate in many applications such as diagnostic tools in the biomedical field (Caro et al., 1971, Droitcour et al., 2009), rescue tools for finding survivors buried under snow cover (Pieraccini et al., 2008), and security devices (Geisheimer et al., 2001). State-of-the-art advances in the field of radar technology have made it possible to design noninvasive sensing devices of vital signs. The effects of the radar-based system on respiratory rate measurement are presented (Schleicher et al., 2013, Lee et al., 2014, Alemaryeen et al., 2018, Hernandez et al., 2022). Noncontact detection characteristic of Doppler radar provides an unobtrusive means of respiration detection and monitoring. This avoids additional preparations, such as physical sensor attachment or special clothing, which can be useful for certain healthcare applications. Furthermore, robustness of Doppler radar against environmental factors, such as light, ambient temperature, interference from other signals occupying the same bandwidth, fading effects, reduce environmental constraints and strengthens the possibility of employing Doppler radar in long-term respiration detection, and monitoring applications such as sleep studies (Lee et al. 2014). Doppler radar can also be used to detect heart rate. The heart rate monitoring performances of antennas used in Doppler radar systems have been studied by researchers (Wang et al. 2015, Nosrati et al. 2017).

In the literature, antenna studies that can be used in radar systems have been conducted. Studies of planar antennas that can be useful in body signal monitoring for biomedical applications have been conducted (Yeap et al., 2021). Studies have been conducted by adopting the slow wave structure of antennas in biomedical applications (Le et al., 2021, Hong et al., 2022). Microstrip antenna performances for body signal applications have been investigated. In this study, off-body and on-body application scenarios have been investigated (Farooq et al., 2022). Patch antenna studies have been conducted for body data communication in wearable technologies (Mohanty et al., 2022). An antenna design fed via a microstrip feedline has been investigated for biomedical applications. The proposed antenna performance has been analyzed with free space. With this analysis, an appropriate antenna design analysis has been made for biomedical applications (Prakash et al., 2023).

When designing radar systems, they should be suitable for the area of use. Receiving and transmitting antennas are important components in radar systems. Antennas such as microstrip, horn and dish are used according to their usage areas (Charvat et al., 2012). In this study, the transmitter and receiver parts of the radar system were chosen as microstrip patch antenna. Microstrip antennas are widely used due to their small size, low cost and various advantages (Nwalozie et al., 2013). Microstrip antennas have been the subject of intensive research due to the inherent qualities of such antennas, such as aerodynamic profile (Ha et al., 2021). These antennas have been used for some time in aircraft, biomedical applications, satellites and military applications (Parthiban et al., 2020, Shen et al., 2017). With the development of wireless communication technology, the importance of microstrip patch antenna has greatly increased. The microstrip patch antenna is used in many applications. The main disadvantages of microstrip antennas are their narrow band and low gain. Therefore, various methods have been developed to improve the antenna's characteristics such as bandwidth, gain and efficiency. It is very important to design antennas appropriately using these methods.

Transmission line equations are used when designing a microstrip antenna (Jayasinghe et al., 2013). These equations alone are not sufficient to create the desired operating conditions of antennas. The desired operating range and return loss of microstrip antennas designed using only these equations may not be measured at the desired value (Islam et al., 2009). Therefore, the designed antenna needs to be improved in accordance with the usage area. Simulations for the design and improvement of the radar antenna were made using the CST program. The effect of geometric size optimization on the designed antenna performance was investigated. By taking advantage of the effects of optimization on antenna performance, factors such as operating frequency, gain and return loss have been tried to be improved. The simulation results of the improved antennas were compared according to the effects of geometric dimensions on the radar antenna, and the effectiveness of geometric dimensions was observed. The antenna geometry was optimized using particle swarm optimization and the performance of the antenna was improved (Islam et al., 2017, Lim et al., 2008). The effects of optimization on the antenna were analyzed in detail in the simulation environment. As a result of the improvements, it was seen that the antenna performance parameters came to better values.

2. Materials and Methods

2.1 Doppler radar system

2.2 Doppler effect

The Doppler effect is used specifically to detect the speed and motion of an object. Doppler radar works by using the information that the waves produced by an object are crushed closely together if they move towards you or

spread more if they are moving away (Pathirana et al., 2012). Compressed waves are higher frequency and higher pitch. In the case of divergence, the propagating waves become low-frequency, low-pitched. For example, a sound wave moving towards us will be heard as a high-pitched sound, and a sound wave moving away from us will be heard as a low-pitched sound.

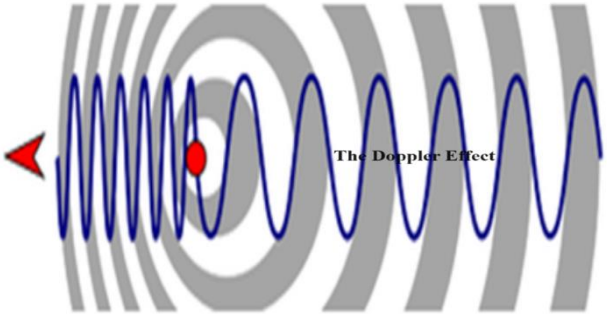


Figure 1. Doppler event

The Doppler event interprets the movement and distance as shown in Figure 1. In other words, the frequency changes caused by the wave between the motion of the target source and the observer are the Doppler effect.

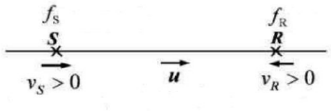


Figure 2. Speed and frequency between target and observer

In Figure 2, the source frequency is shown as f_s; f_R is the observation frequency; f_W is the frequency of the complete wave; V_s is the source's speed; V_R is observer speed; u is the speed of the full wave. 1) If the observer and the source are fixed ($V_s = 0$, $V_R = 0$):

$$f_R = \frac{u}{\lambda} = f_S \tag{1}$$

2) The target is stationary, the observer is moving with velocity ' V_R ' ($V_s = 0$, $V_R \neq 0$):

$$f_R = u + \frac{V_R}{\lambda} = u + V_R\left(\frac{u}{f_W}\right) = \left(1 + \frac{V_R}{u}\right) f_W \tag{2}$$

$$f_W = f_S, f_R = \left(1 + \frac{V_R}{u}\right) f_S \tag{3}$$

3) The observer is stationary, the target is moving with a speed 'V_s' ($V_s \neq 0$, $V_R = 0$):

$$\lambda = uT_S - V_R T_S = u - \frac{V_R}{f_S} \tag{4}$$

$$\lambda = uT_S - V_S T_S = u - \frac{V_S}{f_S} \tag{5}$$

4) When both the target and the observer are moving ($V_s \neq 0$, $V_R \neq 0$):

$$f_W = \left[\frac{1}{\left(1 - \frac{V_S}{u}\right)}\right] f_S \tag{6}$$

$$f_R = \left(1 + \frac{V_R}{u}\right) f_W \tag{7}$$

$$f_R = \left[\frac{\left(1 + \frac{V_R}{u}\right)}{\left(1 - \frac{V_S}{u}\right)}\right] f_S \tag{8}$$

Assuming that the range to the target is 'R', then the total number of waves with a total wavelength ' λ ' from the radar on the two-way path to the target and return is "$2R / \lambda$; Each wavelength is '2π' radians, that is, the two-way total phase change doppler radar system propagation path for proximity sensing can be shown as follows (Gangopadhyaya et al., 2015):

$$\emptyset = 2\pi . \frac{2R}{(\lambda)} = \frac{4\pi R}{\lambda} \tag{9}$$

When the target moves, the phase and 'R' in the radar change. The formula gives the angular frequency phase change rate:

$$\omega_d = \frac{4\pi}{(\lambda)} . \frac{dR}{\lambda} = \frac{4\pi R}{\lambda} \tag{10}$$

$V_r = d_R / d_t$, is the radial velocity (meters per second) or the rate of interval change over time. The vector angle between the target's velocity and the radar is 'Θ', $V_r = V\cos\Theta$, where "V" is the velocity. The angular frequency is $\omega_d = 2\pi f_d$, where 'f_d' is the doppler frequency shift and is expressed as:

$$f_d = \frac{2V_r}{(\lambda)} = \frac{2f_t V_r}{(c)} \tag{11}$$

Basically, radar is an electromagnetic system used to detect the position and distance of an object from the point where it is placed. It works by tracking the signal reflected from objects by radiating energy into space.

2.3 Microstrip Antenna Design and Implementation

The three basic parameters used for rectangular microstrip patch antenna design are:

Working frequency (f_o): The resonant frequency of the antenna must be chosen appropriately. The resonance frequency chosen for the design is 2.4 GHz.

Dielectric constant of the substrate (ε_r): The material chosen for the design is FR-4 silicone, which has a dielectric constant of 4.4. Since the dimensions of the antenna were reduced, a substrate with a high dielectric constant was selected.

Height of dielectric substrate (h): The volume of the microstrip patch antenna should be small. Therefore, the height of the dielectric substrate was chosen as 1.6 mm.

As a result, frequency (f_o) 2.40 GHz, dielectric constant (ε_r) 4.4 and height (h) 1.6 mm were selected for the design.

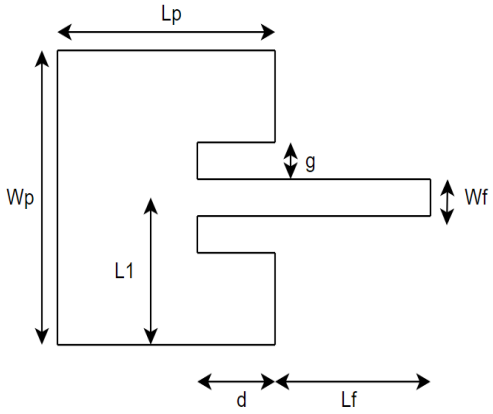


Figure 3. Top view of microstrip patch antenna

Step 1: Calculation of Width (W_p): The width of the microstrip patch antenna is given by equation (12) as below:

$$W_P = \frac{\frac{c}{(2f_o\sqrt{(\varepsilon_r+1)}}}{2} \quad (12)$$

f_o = 2,4 GHz, ε_r = 4,4 and c = 3e8 m/s If we substitute it in the equation as;
We find the patch width (W_p) = 38.01 mm.

Step 2: Calculation of the effective dielectric constant (ε_{reff}): Equation (12) gives the effective dielectric constant as:

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1 + 12\frac{h}{W}\right]^{\frac{1}{2}} \quad (13)$$

ε_r = 4,4, h = 1,6 mm and W_p = 38,01 mm is substituted in the equation as: ε_{reff} = 4,7856 is found as.

Step 3: Effective length calculation: Equation (13) gives the patch length as below:

$$L_{eff} = \frac{c}{2fo\sqrt{\varepsilon_{reff}}} \quad (14)$$

$$\Delta L = \frac{0.412h(\varepsilon_{reff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{reff}-0.258)\left(\frac{W}{h+0.8}\right)} \quad (15)$$

$$L_{eff} = L + 2\,\Delta L \quad (16)$$

If we apply the steps of the equation here and draw L, we will find the patch length. It is found that L_p = 29.42 mm.

Step 4: Calculation of ground plane dimensions (L_g *ve* W_g): The transmission line model can only be applied to infinite ground planes. However, having a practically limited ground plane is essential. So, for this design, the ground plane dimensions are calculated as:

$$L_g\ (Ground\ length) = 6h + L \quad (17)$$

$$W_g\ (Ground\ width) = 6h + W \quad (18)$$

Step 5: Impedance calculation (Z_o):

$$Z_o = \frac{120\pi}{\sqrt{(\varepsilon_{reff}[(\frac{W}{h}+1.393+\frac{2}{3}\ln(\frac{W}{h}+1.444))]}} \quad (19)$$

The purpose of particle swarm optimization used in antenna design is to determine the direction of particle movement in the solution space. This optimization technique assumes that the particles should move towards the best positions from the calculated positions. To update the particle positions at each step, they can be stored in an M x N matrix, where M is the number of particles in the simulation and N is the number of dimensions of the problem (Rahmat-Samii et al., 2003, Kesarwani et al., 2022). In this way, the best particle position can be obtained by performing iteration operations. The best positions are represented by the M x N matrices P = (P_{ij}) and G = (g_{ij}), respectively.
The position and velocity of the particles are updated at discrete intervals.

$$Vuptaded = Vprevious + W_P\,n_1(P\text{-}X) + L_P\,n_2(G\text{-}X) \quad (20)$$

The positions and velocities of the particles are updated at discrete intervals in the range $0 \le n_{1,2} \le 1$, W_p and L_p determine the influences on the trajectories of the particle (Jin et al., 2008). Finally, the particles move according to the desired best position.

$$Vuptaded = Vprevious + V.\Delta t \quad (21)$$

Where At is either a unit time step.

The patch antenna and array antennas realized as a result of the steps applied for the microstrip antenna design are shown in figure 4.

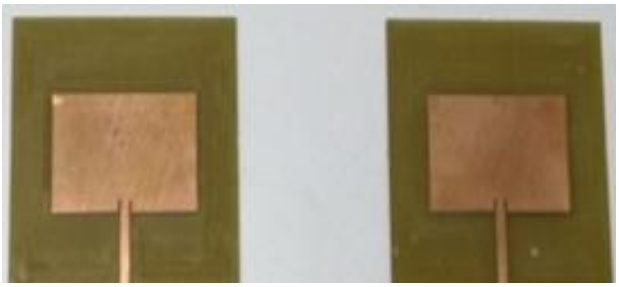


Figure 4. Top view of microstrip patch antenna

2.3 Microstrip Antenna Design and Implementation Components of the Radar System

The radar system consists of six components:

Waveguides: Waveguides are transmission lines of radar signals.

Transmitter Antenna: The transmitter antenna uses a power amplifier or a power oscillator. The signal is first

generated using a waveform generator and then amplified in the power amplifier.

***Receiver Antenna**:* It is used to receive the incoming signal. The incoming signal is sent to the processor via the filter circuit.

Threshold Decision: The output of the receiver is compared with a threshold to detect the presence of any object. If the output is below any threshold, noise is assumed.

Microwave Part: At this stage, the signal flow of the receiving and transmitting antennas is provided by the Doppler effect.

Low Pass Filter Circuit: The signal obtained from the microwave part is filtered and the Doppler effect is observed at the output.

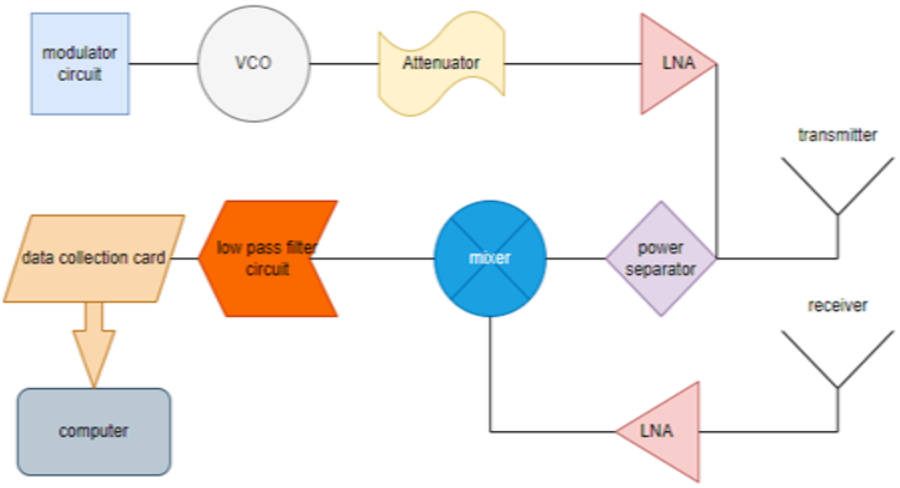


Figure 5. Flow diagram of radar system

The basic operation diagram of the radar system is given in Figure 5. The signal obtained from the modulator is transmitted to the voltage-controlled oscillator (VCO), providing a continuous signal. Using the power splitter microwave element, the signal is split into two, one sent to the mixer and the other to the amplifier (LNA). By amplifying the signal with the amplifier, the signal is sent from the transmitting antenna towards the target. The signal reflected from the target is amplified by the amplifier and sent to the mixer. The difference created by the modulation process in the mixer is sent to the filter circuit. The cut-off frequency is obtained in the filter circuit and the process is completed by interpreting the data in the computer environment.

3. Results and Discussions

The best antenna performance result was tried to be obtained by changing the geometric dimensions of the antenna applied on the microstrip patch. In this section, the patch antenna designed at the desired values is optimized with the radar system.

While the antenna designed in Figure 6 was at 2.36 GHz, it reached 2.40 GHz after mathematical changes were made in the antenna dimensions. The desired operating frequency is thus obtained. The return container increased from -19 dB to -28 dB, and a better result was obtained compared to the previous one.

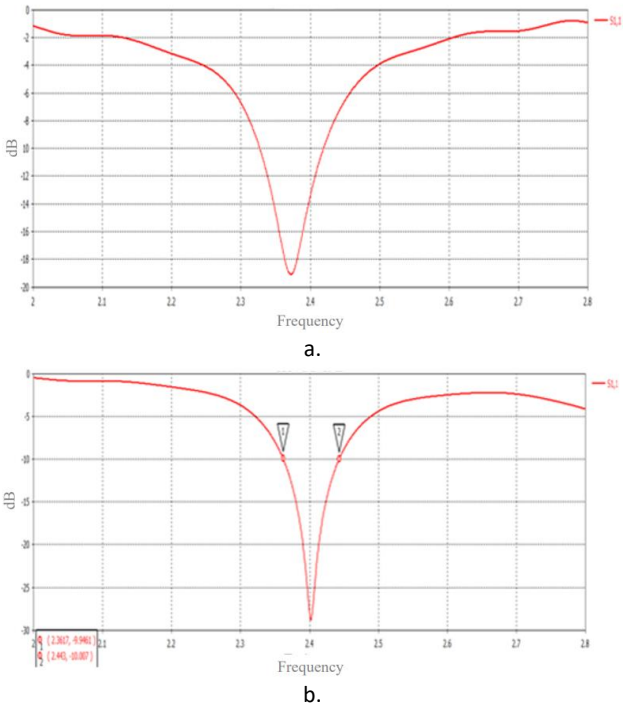
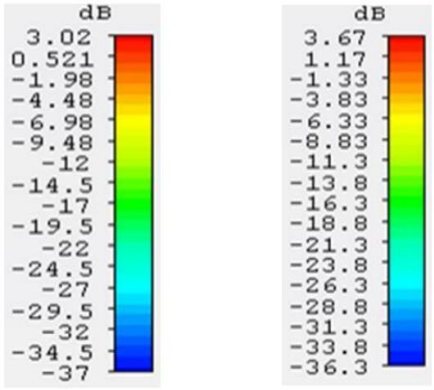


Figure 6. Comparison of s11 parameters of antennas before and after optimization (a: first; b: second)

The gain state of the first state of the antenna designed in Figure 7 has been increased by making a mathematical change in geometric dimensions. At this stage, the radar antenna gain was increased from 3.02 dB to 3.67 dB.

The optimized version of the radar system to 2.40 GHz operating frequency is as shown in Figure 5. A continuous

signal was obtained by connecting the 3-volt ramp signal produced by the modulator circuit to the voltage-controlled oscillator (VCO).



(a) (b)

Figure 7. Comparison of s11 parameters of antennas before and after optimization (a: first; b: second)

It is attenuated as the RF signal from the VCO. Then, the RF signal was amplified by the amplifier (LNA) and sent to the power splitter. An attenuator was used here to protect the amplifier from the high-power RF signal. In order for the attenuated signal from the amplifier to be carried to the target at a certain distance via the transmitting antenna, it must have sufficient power. However, the signal from the voltage-controlled oscillator is not strong enough. In addition, since the power of the signal reflected from the target will be very low, it will not be possible to reach the receiving antenna and be processed by the mixer. Therefore, amplifiers were used in both transmitting and receiving antennas. The amplifier was used before sending the signal to the transmitting antenna and after the receiving antenna. As seen in Figure 5, two amplifiers are used in the system. The signal reflected from the target via the receiving antenna was modulated with the reference signal 2.40 GHz in the mixer circuit. Therefore, the RF signal generated at the output of the voltage oscillator was sent to the target via the transmitting antenna and was also sent to the mixer to perform the multiplication process. The Doppler frequency was obtained by connecting the signal obtained from the mixer to the filter circuit. The signal transmitted to the opamp input part was sent to the processor after filtering.

The finished installation and testing of the radar system is shown in Figure 8. The receiver and transmitter antennas of the system are symmetrically connected to the target. Additionally, the filter output was connected to the digital-to-analog converter to the computer via the USB port.

It was tested by placing an aluminum-coated barrier moved 50 cm away from the transmitting and receiving antennas. The signals coming from the receiving and transmitting antennas were filtered in the radar system and the movement speed of the signal was observed in the time domain.

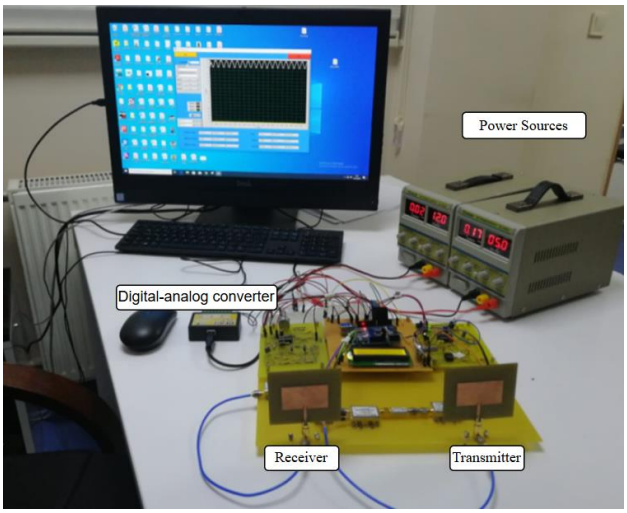


Figure 8. Connection of radar system to computer with digital-analog converter

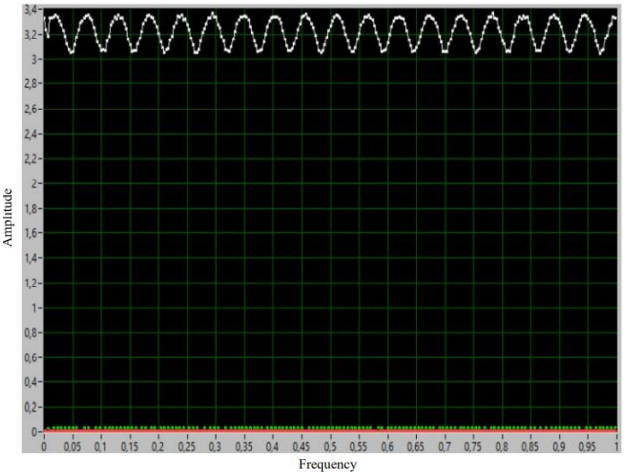


Figure 9. Measurement of target object at long distance

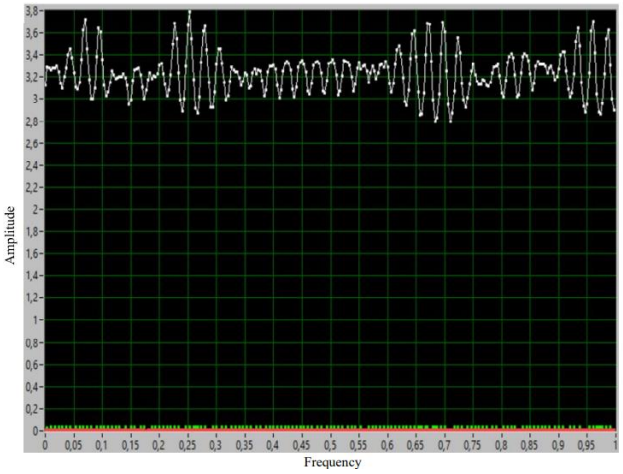


Figure 10. Measurement of target object at close range

The target object placed in front of the system was moved forward and backward. The target object's movement distance was set to 5 cm. As the target moves away, the amplitude in the time domain (3-3.4) decreases as seen in

Figure 9. In Figure 10, it is observed that the amplitude increases in the time domain (2.8-3.8) as the target system gets closer. As a result of the movement of the target object in front of the system, a change of 0.4 units in the amplitude was observed. Thus, the forward and backward movement of the target object was determined.

4. Conclusions

In this study, it was aimed to design a doppler radar system that can be used in biomedical applications. The design and optimization of the antennas were made with the CST simulation program. The operating frequency of the antennas has been increased from 2.36 GHz to 2.4 GHz. Antenna gain increased from 3.02 dB to 3.67 dB. The return loss was reduced from -19 dB to -28 dB. The antennas have been optimized and their performance has been improved. Synchronization of the radar system with microwave materials has been achieved. Finally, the system was made operational using the radar system and a data acquisition card. In the presence of an object moved back and forth in front of the realized antennas (at a distance of 50 cm), the movements of this object were examined on the computer screen. Changes in the time domain amplitude were observed on the computer screen with the object movements in the forward and backward directions. It was observed that the amplitude measured at far distance was between 3 and 3.4, while the amplitude measured at close distance was between 2.8 and 3.8. As a result, object movements have been detected and it has been determined that these movements can be interpreted according to the changes in amplitude. The radar system is intended to be used in future studies to monitor basic life functions such as respiratory rate and heart rate detection.

Declaration of Ethical Standards
The authors declare that they comply with all ethical standards.

Authorship Contribution Statement
Author 1: Research, Resources, Experimentation, Writing – original draft visualization, Writing – original draft, Analysis and interpretation
Author 2: Research, Resources, supervision, and writing – review & editing, consultancy.

Declaration of Competing Interest
The authors have no conflicts of interest to declare with respect to the content of this article.

Data Availability Statement
All data generated or analyzed during this study are included in this published article.

References

Alemaryeen, A., Noghanian, S., and Fazel-Rezai, R. (2018). Antenna effects on respiratory rate measurement using a UWB radar system. *IEEE Journal of Electromagnetics, RF and Microwaves in Medicine and Biology,* **2**(2), 87-93. https://doi.org/10.1109/JERM.2018.2813534

Caro, C. G., and Bloice, J. A. (1971). Contactless apnoea detector based on radar. *The Lancet,* **298**(7731), 959-961. https://doi.org/10.1016/S0140-6736(71)90274-1

Charvat, G., Williams, J., Fenn, A., Kogon, S., and Herd, J. (2012). Build a Small Radar System Capable of Sensing Range, Doppler, and Synthetic Aperture Radar Imaging. *2012 IEEE Radar Conference,* **45**, 4445. https://doi.org/10.1109/RADAR.2012.6212126

Droitcour, A. D., Seto, T. B., Park, B. K., Yamada, S., Vergara, A., El Hourani, C., and Boric-Lubecke, O. (2009). Non-contact respiratory rate measurement validation for hospitalized patients. *In 2009 Annual International Conference of the IEEE Engineering in Medicine and Biology Society,* **89**(1239), 4812-4815. https://doi.org/10.1109/IEMBS.2009.5332635

Farooq, U., & Rather, G. M. (2022). A miniaturised Ka/V dual band millimeter wave antenna for 5G body centric network applications. *Alexandria Engineering Journal*, ***61***(10), 8089-8096. https://doi.org/10.1016/j.aej.2022.01.044

Gangopadhyaya, M., Mukherjee, P., Sharma, U., Gupta, B., and Manna, S. (2015). Design Optimization of Microstrip fed Rectangular Microstrip Antenna Using Differential Evolution Algorithm. In *2015 IEEE 2nd International Conference on Recent Trends in Information Systems,* **6**(364), 49-52. https://doi.org/10.1109/ReTIS.2015.7232851

Geisheimer, J., and Greneker, E. F. (2001). A non-contact lie detector using radar vital signs monitor (RVSM) technology. *IEEE Aerospace and Electronic Systems Magazine,* **16**(8), 10-14. https://doi.org/10.1109/62.942213

Ha, Y., Jung, J. I., Lee, S., & Pyo, S. (2021). Extremely low-profile monopolar microstrip antenna with wide bandwidth. *Sensors*, ***21***(16), 5295. https://doi.org/10.3390/s21165295

Hernandez-Aguila, M., Olvera-Cervantes, J. L., Perez-Ramos, A. E., and Corona-Chavez, A. (2022). Methodology for the determination of human respiration rate by using Doppler radar and Empirical Modal Decomposition. *Scientific Reports,* **12**(1), 8675. https://doi.org/10.1038/s41598-022-12726-z

Hong, J., Fan, Y., & Liu, X. (2022, May). Dual-mode implantable antenna with dual bands for omnidirectionally in-body and circularly polarized

off-body communications. In *2022 IEEE MTT-S International Microwave Biomedical Conference (IMBioC)* (pp. 102-104). IEEE. https://doi.org/10.1109/IMBioC52515.2022.9790282

Islam, M. T., Mahmud, M. Z., Misran, N., Takada, J. I., & Cho, M. (2017). Microwave breast phantom measurement system with compact side slotted directional antenna. *IEEE access*, ***5***, 5321-5330. https://doi.org/10.1109/ACCESS.2017.2690671

Islam, M. T., Moniruzzaman, M., Misran, N., & Shakib, M. N. (2009). Curve Fitting Based Particle Swarm Optimization for UWB. *Journal of Electromagnetic Waves and Applications,* **23**(17-18), 2421-2432. https://doi.org/10.1109/iceei.2009.5254724

Jayasinghe, J. M. J. W., and Uduwawala, D. N. (2013). Optimization of the performance of patch antennas using genetic algorithms. *Journal of the National Science Foundation of Sri Lanka,* **41**(2), 113-120. https://doi.org/10.4038/jnsfsr.v41i2.5705

Jin, N., & Rahmat-Samii, Y. (2008). Particle swarm optimization for antenna designs in engineering electromagnetics. *Journal of Artificial evolution and applications*, ***2008***(1), 728929. https://doi.org/10.1155/2008/728929

Kesarwani, A. K., Yadav, M., Singh, D., & Gautam, G. D. (2022). A review on the recent applications of particle swarm optimization & genetic algorithm during antenna design. *Materials Today: Proceedings*, ***56***, 3823-3825. https://doi.org/10.1016/j.matpr.2022.02.200

Le, T. T., & Yun, T. Y. (2021). Wearable dual-band high-gain low-SAR antenna for off-body communication. *IEEE Antennas and Wireless Propagation Letters*, ***20***(7), 1175-1179. https://doi.org/10.1109/LAWP.2021.3074641

Lee, Y. S., Pathirana, P. N., Steinfort, C. L., and Caelli, T. (2014). Monitoring and analysis of respiratory patterns using microwave doppler radar. *IEEE journal of translational engineering in health and medicine,* **2**, 1-2. https://doi.org/10.1109/JTEHM.2014.2365776

Lim, H. B., Nhung, N. T. T., Li, E. P., & Thang, N. D. (2008). Confocal microwave imaging for breast cancer detection: Delay-multiply-and-sum image reconstruction algorithm. *IEEE Transactions on Biomedical Engineering*, ***55***(6), 1697-1704.

Lin, A., and Ling, H. (2007). Doppler and direction-of-arrival (DDOA) radar for multiple-mover sensing. *IEEE transactions on aerospace and electronic systems,* ***43***(4), 1496-1509. https:/doi.org/10.1109/TAES.2007.4441754

Mensa D., Halevy L. and Wade S.G. (1983). Coherent Doppler tomography for microwave imaging. *Proceedings of the IEEE,* **71**(2), 254-261. https:/doi.org/10.1109/PROC.1983.12563

Mohanty, M. N., & Mahapatra, S. (2022). Multiband hexagonal patch antenna for high data rate wearable applications. *Iranian Journal of Science and Technology, Transactions of Electrical Engineering*, ***46***(4), 925-934. https://doi.org/10.1007/s40998-022-00516-2

Nosrati, M., and Tavassolian, N. (2017). Effects of antenna characteristics on the performance of heart rate monitoring radar systems. *IEEE Transactions on Antennas and Propagation,* **65**(6), 3296-3301. https://doi.org/10.1109/TAP.2017.2694861

Nwalozie, G. C., Okezie, C. C., Ufoaroh, S. U., and Nnebe, S. U. (2013). Design and Performance Optimization of a Microstrip Antenna. *International Journal of Engineering and Innovative Technology (IJEIT),* **2**, 2277-3754. https://doi.org/10.7763/ijmo.2013.v3.303

Parthiban, P., Seet, B. C., & Li, X. J. (2020). An ultra-rugged UHF RFID reader antenna: A new design for convention center loading docks [wireless corner]. *IEEE Antennas and Propagation Magazine*, ***62***(1), 84-95. https://doi.org/10.1109/MAP.2019.2946560

Pathirana, P. N., Herath, S. C., and Savkin, A. V. (2012). Multitarget tracking via space transformations using a single frequency continuous wave radar. *EEE transactions on signal processing,* **60**(10), 5217-5229. https://doi.org/10.1109/TSP.2012.2206588

Pieraccini, M., Luzi, G., Dei, D., Pieri, L., and Atzeni, C. (2008). Detection of breathing and heartbeat through snow using a microwave transceiver. *IEEE Geoscience and Remote Sensing Letters,* **5**(1), 57-59. https://doi.org/10.1109/LGRS.2007.907421

Prakash, S., Kumar, K., Arulaalan, M., & Kalaivanan, M. (2023, April). A hybrid cubic dielectric loaded tri-band antenna for biomedical applications. In *2023 2nd International Conference on Smart Technologies and Systems for Next Generation Computing (ICSTSN)* (pp. 1-5). IEEE. https://doi.org/10.1109/ICSTSN57873.2023.10151556

Rahmat-Samii, Y., Gies, D., & Robinson, J. (2003). Particle swarm optimization (PSO): A novel paradigm for antenna designs. *URSI Radio Science Bulletin*, ***2003***(306), 14-22. https://doi.org/10.1093/ietcom/e91-b.2.527

Schleicher, B., Nasr, I., Trasser, A., and Schumacher, H. (2013). IR-UWB radar demonstrator for ultra-fine movement detection and vital-sign monitoring. *IEEE transactions on microwave theory and techniques,* **61**(5), 2076-2085. https://doi.org/10.1109/TMTT.2013.2252185

Shen, S., Chiu, C. Y., & Murch, R. D. (2017). A dual-port triple-band L-probe microstrip patch rectenna for ambient RF energy harvesting. *IEEE Antennas and Wireless Propagation Letters*, ***16***, 3071-3074. https://doi.org/10.1109/LAWP.2017.2761397

Skolnik M. (2002). Role of radar in microwaves. *IEEE Transactions on Microwave Theory and Techniques,* **50**(3), 625-632. https:/doi.org/10.1109/22.989947

Wang, S., Pohl, A., Jaeschke, T., Czaplik, M., Köny, M., Leonhardt, S., and Pohl, N. (2015). A novel ultra-wideband 80 GHz FMCW radar system for contactless monitoring of vital signs. *In 2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC),* **70**(2940), 4978-4981. https://doi.org/10.1109/EMBC.2015.7319509

Yeap, K. H., Tan, E. M. F., Hiraguri, T., Lai, K. C., & Hirasawa, K. (2021). A multi-band planar antenna for biomedical applications. *Frequenz*, ***75***(5-6), 221-228. https://doi.org/10.1515/freq-2020-0079