VOLTRUN Company

Contactless Vital Sign Monitor

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Executive Summary

VoltRun designed the contactless vital sign monitoring system for use in natural disasters, military operations, and patient monitoring. The system provides important information about respiration in a 2m x 2m area with curtains around it, without a camera. It can detect whether there is a living being in the specified area within 300 seconds. It also informs the user about breath per minute (BPM) and breathing mode. It is highly suitable for use cases where physical access is limited or undesirable due to safety, privacy, or operational constraints.

The Software-Defined Radio (SDR) unit, the signal processing unit, the mechanical respiration simulator, and the user interface unit are the four subsystems that make up the system architecture. These elements work together to provide real-time analysis, continuous RF-based monitoring, and user-friendly interaction.

The SDR unit is a unit that provides continuous wave (CW) signal transmission and reception, consisting of Adalm Pluto and 2 patch antennas. The antennas and Adalm Pluto are connected with SMA cables. The antennas are directional, and their positions are adjusted to minimize mutual interference. The reason for the directionality of the antennas is that the vital sign scan will be done in one direction. It transmits the signal, which is the difference in the phase, reflected as a result of chest movement, to the signal processing unit.

The signal processing unit receives and processes the signal that has undergone a phase difference due to the Doppler shift coming from the SDR unit. The difference created by the phase difference gives us information about chest movement in terms of distance. It detects chest movement through the data processed as a result of the phase change. Vital sign detection, breath per minute (BPM), and breathing mode (normal, fast, apnoea) classifications are made using the detected movement data.

The mechanical respiration simulator was made for testing the system. Chest movement was modeled using a linear actuator. The linear actuator was controlled using a motor driver and a microprocessor. The simulator has 3 different modes: normal, fast, and apnoea breathing. These modes are controlled by binary-coded switches on the simulator. It works with batteries without using an external power supply. To gain a human-like appearance, agar-salt solution was added to the end of the linear actuator in the simulator with the help of a platform. The content of this solution was adjusted according to human permittivity.

The user interface unit is the section where the data in the signal processing unit is presented to the user. The user is presented with a breathing chart, whether a living being is detected within the scanned area, and if so, BPM and breathing mode information. The interface is user-friendly and is very easy and practical to use, with start and stop buttons. This subsystem is essential to enabling the system's sophisticated technology to be usable and accessible in practical situations.

Extensive testing has verified that every system component complies with the design requirements and operates consistently over a range of configurations and distances. The system has proven to have quick reaction times, high detection accuracy, and strong classification reliability. The VOLTRUN Contactless Vital Sign Monitor is a technically sound and reasonably priced solution that was created by a multidisciplinary team of engineers with expertise in RF systems, signal processing, embedded systems, and mechanical design. It offers a creative and flexible platform for future advancements in remote health monitoring and has the potential to be widely implemented in both the defense and civilian sectors.

Introduction

Motivation of the Project

The project aims to meet crucial demands in healthcare and emergency applications by developing a contactless vital sign monitoring system. This project seeks to provide a reliable and flexible system that avoids the requirement for direct contact while providing accurate and quick detection. By emphasising a camera-free system, it aims to improve safety, minimize operational complexity, and provide a low-cost method of monitoring vital signs.

Literature/Market Survey (State of the Art)

Raheel et al. provide a comprehensive overview of recent advancements in contactless vital sign monitoring in both academic and market contexts. The authors identify 32 distinct contactless and camera-free techniques for monitoring vital signs within this field. These approaches are explored across several studies, including PhaseBeat, utilizing the phase difference concept to estimate respiration rate, as we do. The systems they explore employ a range of algorithms, including wavelet transforms, Fast Fourier Transform (FFT) -based detection, and envelope detection, among others. [1]

In the commercial sector, we reference several notable products. DAR (Duvar Arkası Radar) from STM is used to detect vital signs through the wall [2]. Another innovative product is Xethru by Novelda, a UWB IR radar system that calculates respiratory rates using pulse Doppler radar. [3] SleepMinder, developed by Irish firm BiancaMed, is a biosensor aimed at assessing the apnoea-hypopnoea index in patients. [4] WiBreath works on Wi-Fi bands to detect human breathing, while Analog Devices offers the ADXL accelerometer, a 3-axis MEMS device designed to monitor a patient's chest movements through bed vibrations. [5]

Solution Method

The VOLTRUN Contactless Vital Sign Monitor's signal processing strategy, which detects respiratory motion accurately without physical contact, is based on the phase shift analysis method. This method makes use of the idea that any slight movement, like shifting the chest wall while breathing, causes a phase modulation in the reflected signal when a continuous-wave (CW) radio frequency (RF) signal is directed toward the subject. Phase shift analysis tracks displacement directly, which is more susceptible to noise and multipath interference, or frequency shift detection, which estimates velocity. Since the chest normally moves only a few millimeters per second during respiratory monitoring, this is especially crucial.

In practice, a sinusoidal signal at 300 Hz modulated by a carrier signal (4.6 GHz) is used in this system and is sent through a patch antenna. The received signal has a phase term that changes over time as a result of the path length changing when this wave bounces off a moving object, like the chest. By multiplying the received signal by the complex conjugate of the reference signal, the system isolates the phase information and carries out complex demodulation. By "unwrapping" this raw phase data, discontinuities are eliminated, and a smooth, continuous signal that corresponds to chest displacement is reached.

Respiration is defined by a periodic waveform in the phase signal, where each peak typically represents an inhalation. The respiration rate is calculated by measuring the average time intervals between successive peaks, which is expressed in breaths per minute (BPM). Furthermore, based on the computed BPM, the system divides the breathing mode into three predetermined categories—normal breathing, fast breathing, and apnea. This technique is beneficial because it can function reliably in cluttered or obstructed areas, such as behind opaque curtains or debris, in addition to being sensitive to even the smallest movements. Because of its precision, robustness, and real-time capabilities, phase shift analysis is the ideal method for the system's intended applications in disaster, medical, and defense scenarios.

Scope and Organization of the Report

This report presents the complete design, development, testing, and validation processes of the VOLTRUN Contactless Vital Sign Monitoring System. The system was developed to detect human presence and monitor respiratory activity in a confined space without any physical contact, using radio frequency (RF) signal analysis. The report documents each stage of the project, from the initial motivation and literature research to technical implementation, subsystem integration, and final evaluation through real-world testing.

The structure of the report is organized as follows:

Executive Summary: Provides a concise overview of the project objectives, system architecture, key features of each subsystem, and validation results.
Introduction and Motivation: Explains the need for contactless monitoring systems in healthcare, rescue operations, and defense applications, and outlines the project's main goals.
Literature and Market Survey: Reviews academic studies and commercial solutions related to non-contact vital sign monitoring, highlighting the novelty and technical advantages of the VOLTRUN system.
Solution Method: The system employs phase shift analysis to detect respiratory motion by measuring the continuous phase variations in reflected RF signals caused by chest displacement during breathing.
Problem Statement: Identifies the key engineering and operational challenges encountered during the design phase, including signal attenuation, phase noise, and real-time processing constraints.
Evaluation of Requirement Compliance: Details how each defined system requirement has been fulfilled through specific design choices, implementation strategies, and test results.
System Design: Explains the four main subsystems—SDR Unit, Signal Processing Unit, Mechanical Respiration Simulator, and User Interface—and how they interact to deliver accurate, real-time monitoring.
Subsystem Descriptions: Provides in-depth technical information on the design, components, and functions of each subsystem, with visual references such as diagrams and flowcharts.
Test Results: Presents empirical performance data obtained from three sets of experiments: presence detection, BPM estimation, and breathing mode classification. Accuracy, reliability, and response time are analyzed in detail.
Power Analysis: Discusses the power consumption characteristics of both the SDR and simulator units, demonstrating their suitability for low-power applications.
Cost Analysis: Breaks down the development and final product costs, including materials, components, and engineering efforts.
Deliverables: Lists the tangible outputs of the project, including hardware, software, technical documentation, and source code.
Discussions: Addresses safety concerns, environmental impact, and potential societal applications of the system, especially in medical, emergency, and defense domains.
Conclusion: Summarizes the achievements of the project, confirms successful requirement fulfillment, and highlights future work opportunities and potential for real-world deployment.
Appendices: Includes detailed performance test procedures and results, as well as the full User Manual, which provides operational instructions, troubleshooting guidance, and maintenance information.

Problem Statement

Clinical settings, emergency response, earthquake rescue operations, and military applications are among the majority of high-stakes situations where accurate, non-contact vital sign monitoring is vital. In medical settings, minimizing direct physical contact with patients is frequently required to avoid issues like cross-contamination or skin irritation. Finding survivors who are buried beneath debris quickly can significantly improve the effectiveness of rescue efforts during natural disasters like earthquakes. Similar to this, precise and non-intrusive personnel monitoring techniques greatly aid military operations. This project aims to create a reliable, camera-free system that can effectively monitor vital signs without physical contact to satisfy these various and pressing needs.

The accurate detection of minute respiratory movements is one of the main technical difficulties in creating such a system. It is necessary to use highly sensitive and accurate sensing technologies because the chest wall usually exhibits displacements between 2 and 5 millimeters per second, which correspond to respiratory frequencies between 0.2 and 1 Hz [6]. The combination of sophisticated signal processing algorithms, sophisticated sensing hardware, and specialized data encoding techniques is necessary to achieve the necessary level of precision. The task is further complicated by the requirement to detect reflected signals through physical barriers like walls, opaque curtains, or collapsed structures. To overcome these obstacles, Software Defined Radio (SDR) systems must be used in conjunction with carefully designed, high-performance antennas to maximize signal strength, directionality, and stability while reducing cross-interference.

To precisely monitor respiratory activity, the suggested system uses phase difference analysis between the transmitted and reflected radio frequency (RF) signals. Finer spatial resolution requires operation in high-frequency bands, especially above 3 GHz. Higher frequencies are more vulnerable to signal attenuation by intervening materials because they naturally produce lower signal amplitudes. To guarantee dependable system operation, an ideal balance between frequency selection and attenuation management must be achieved.

Efficient filtering and interpretation of reflected RF signals are essential for precise measurement and classification of respiratory behavior. The creation of a reliable peak detection algorithm that can examine phase variations is a crucial prerequisite. This algorithm needs to have high sensitivity and precision in order to measure breathing rates, chest wall displacement, and fine respiratory movements.

A mechanical respiration simulator that mimics the motion of the human chest wall must also be created in order to aid in system validation and improvement. Across a range of displacement amplitudes and frequencies, this simulator should be able to faithfully replicate a variety of breathing dynamics, such as regular breathing, apnea, and irregular patterns. The technical challenges of creating such a simulator are evident, especially concerning behavioral fidelity and calibration accuracy.

A multidisciplinary effort combining knowledge of RF engineering, antenna design, algorithm development, and mechanical systems simulation is required for the successful implementation of this system. To guarantee a sensitive, dependable, and flexible solution appropriate for a range of operational scenarios, the project's goals will need to be met through meticulous system design, extensive testing, and ongoing iteration.

Evaluation of Requirement Compliance

Our objectives and requirements are tabulated in Table 1.

Table 1: Evaluation of Requirement Compliance

Requirement	***Requirement Fulfillment Method***
The system should be camera-free, and all sensing equipment should be placed on the same side and outside the opaque curtain.	*During the detection process, Adalm Pluto and the antennas are outside the curtained area and on the same side.*
After the device starts to scan, if there is a human being in the area surrounded by curtains, this should be detected within 300 seconds.	*Total scanning time consists of 30 seconds of stabilization in addition to ten consecutive steps of 10 seconds, scanning the 2m edge, which adds up to 130 seconds.*
Detect the presence of live beings in at least four separate places throughout a 2m × 2m test area covered by an opaque curtain.	*There is no restriction on the system detecting chest movement, except that the distance from the antenna should not exceed 2 meters. Detection can be made at all points within a 2m x 2m area.*
The chance of detection should be at least 80%, with an acceptable risk of false alarm.	*The system exceeds 95% accuracy in detecting chest movements, and this level of precision is sufficient to meet the 80% accuracy requirement for BPM calculation.*
The simulator should be able to simulate chest movement for 3 different breathing modes (normal breathing, fast breathing, and apnoea).	*Simulator can simulate 3 different breathing modes, namely normal, fast, and apnoea, by using the linear actuator.*
The simulator should not contain an external power supply.	*The simulator uses batteries as a power supply.*
The system should be able to calculate the respiration rate of the chest movement it detects.	*The system obtains BPM data by detecting the maximum and minimum points.*
The system should be able to classify the breathing mode according to the respiration rate it detects.	*The system determines the breathing mode based on the measured breaths per minute (BPM).*
The system should present to the user the breathing rate it calculates and the breathing mode it classifies as a result of the breathing rate.	*The system will present the calculated BPM value and the breathing mode classification made according to this BPM value to the user on the PC screen.*

System Design

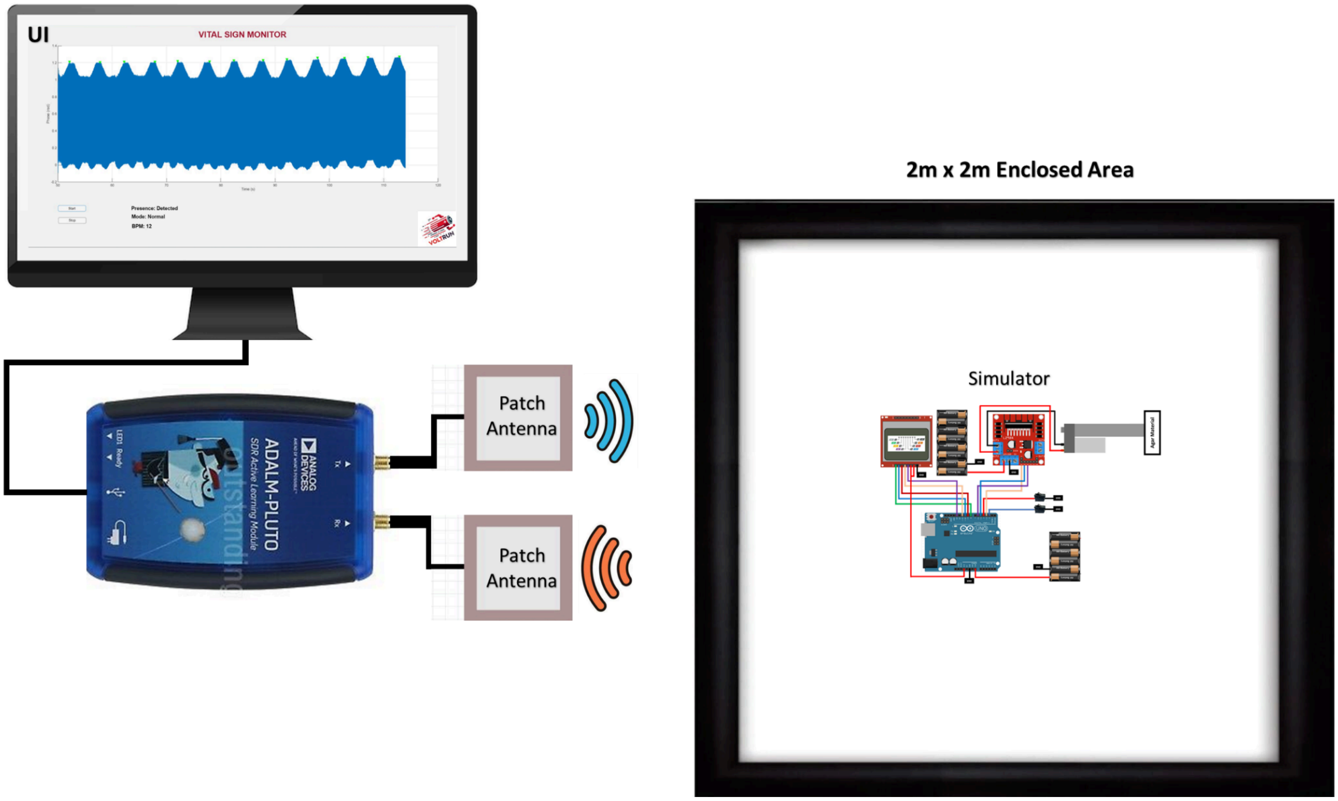

Figure 1: *Vital Sign Monitor Connections and Application Field*

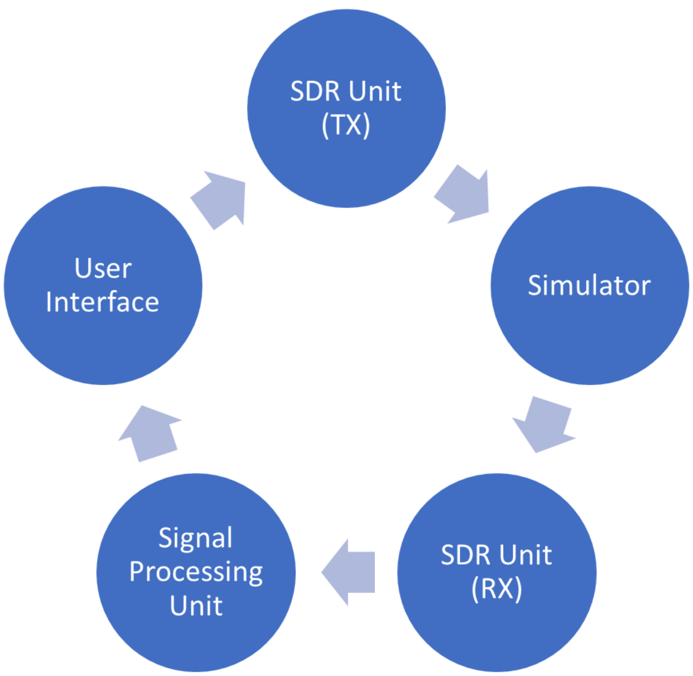

Figure 2: *Vital Sign Monitor Working Principle*

The system is composed of four main subsystems, each responsible for a critical function that enables accurate and real-time contactless vital sign monitoring:

- **Software-Defined Radio (SDR) Unit:**
  This subsystem transmits and receives continuous-wave (CW) radio signals using a pair of directional patch antennas. The antennas are spatially aligned to maximize sensitivity to phase changes caused by chest wall motion during respiration, while minimizing mutual interference. The SDR unit captures the raw signal data and sends it to the processing unit.

  Elements in the unit:
    - ❖ Adalm Pluto
    - ❖ 2 Patch Antennas
    - ❖ USB Cable
    - ❖ 2 SMA Cables

- **Signal Processing Unit:**
  Implemented on a host computer, this unit demodulates the received RF signals and applies phase unwrapping algorithms to extract respiratory motion. It calculates breaths per minute (BPM) and classifies breathing into three modes: normal, fast, and apnoea. This processing ensures robust and real-time physiological assessment.

  Elements in the unit:
    - ❖ Computer
    - ❖ MATLAB
    - ❖ Source Code

- **Mechanical Respiration Simulator:**
  Designed for system testing and validation, the simulator consists of a linear actuator controlled by a microcontroller. An agar-based phantom simulates human chest motion, replicating the dielectric properties of human tissue. Breathing modes are selected via binary-coded switches, and the unit is powered internally, allowing for portable and independent operation.

  Elements in the unit:
    - ❖ Linear Actuator
    - ❖ Motor Driver
    - ❖ Arduino Uno
    - ❖ 2 Batteries
    - ❖ LCD Screen
    - ❖ 2-bit mode selector (2 buttons)
    - ❖ Agar solution and its platform

- **User Interface (UI) Unit:**
  The UI is a standalone executable application that enables users to control the system and view real-time data. It displays the unwrapped phase signal, peak detection, BPM calculation, and classified breathing mode. The interface simplifies user interaction and ensures system usability by non-technical personnel.

  Elements in the unit:
    - ❖ mlapp

These subsystems operate in coordination to deliver a reliable, noninvasive solution for vital sign detection, suitable for various operational scenarios, from healthcare to disaster response.

SDR Unit

The Software-Defined Radio (SDR) Unit serves as the primary sensing subsystem of the contactless vital sign monitoring system. In this project, the SDR platform used is the Analog Devices ADALM-PLUTO, which is configured to operate at a carrier frequency of 4.6 GHz. This frequency was selected to provide sufficient spatial resolution for detecting subtle respiratory-induced chest movements. The SDR unit continuously transmits a continuous-wave (CW) signal and receives its reflection from the target area.

Two directional patch antennas are connected to the SDR—one to the transmit (TX) port and the other to the receive (RX) port. These antennas are positioned and separated carefully to minimize mutual interference and optimize sensitivity to small phase changes caused by chest displacement. The reflection of the transmitted signal carries respiration-related phase modulations, which are essential for accurate signal analysis. The radiation pattern of the typical patch antenna can be seen in Figure 2.

The ADALM-PLUTO SDR communicates with the host computer via a USB-based serial connection, which also provides the power supply required for operation, eliminating the need for an external power source. The SDR is controlled and configured through MATLAB scripts, allowing for real-time signal acquisition, frequency tuning, gain adjustment, and data streaming. The raw IQ data collected by the SDR is forwarded directly to the signal processing unit, where it undergoes phase demodulation and analysis to extract physiological metrics such as breaths per minute (BPM) and breathing mode classification.

Overall, the SDR unit functions as the front-end radar sensor of the system and is critical for enabling contactless detection of respiratory motion through its precise RF transmission and reception capabilities.

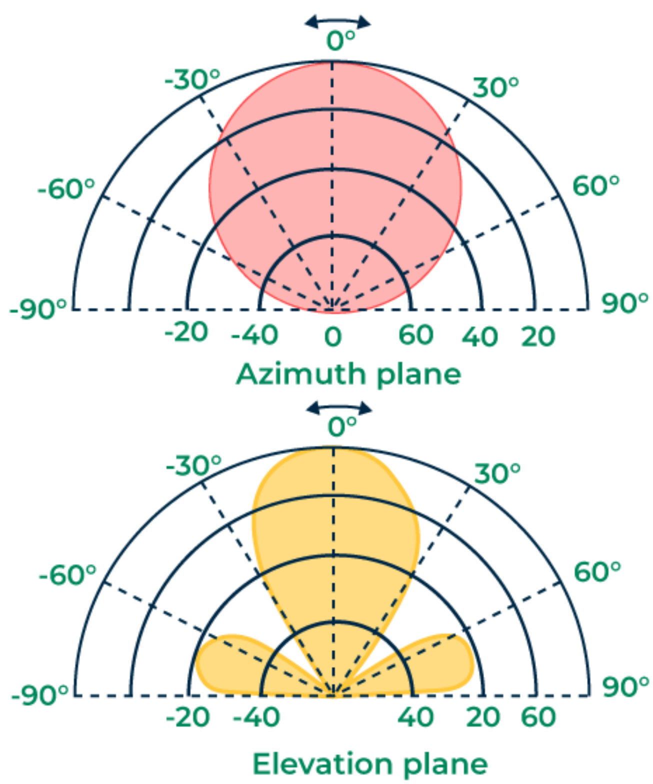

Figure 2: *Radiation Pattern of Typical Patch Antenna [7]*

Signal Processing Unit

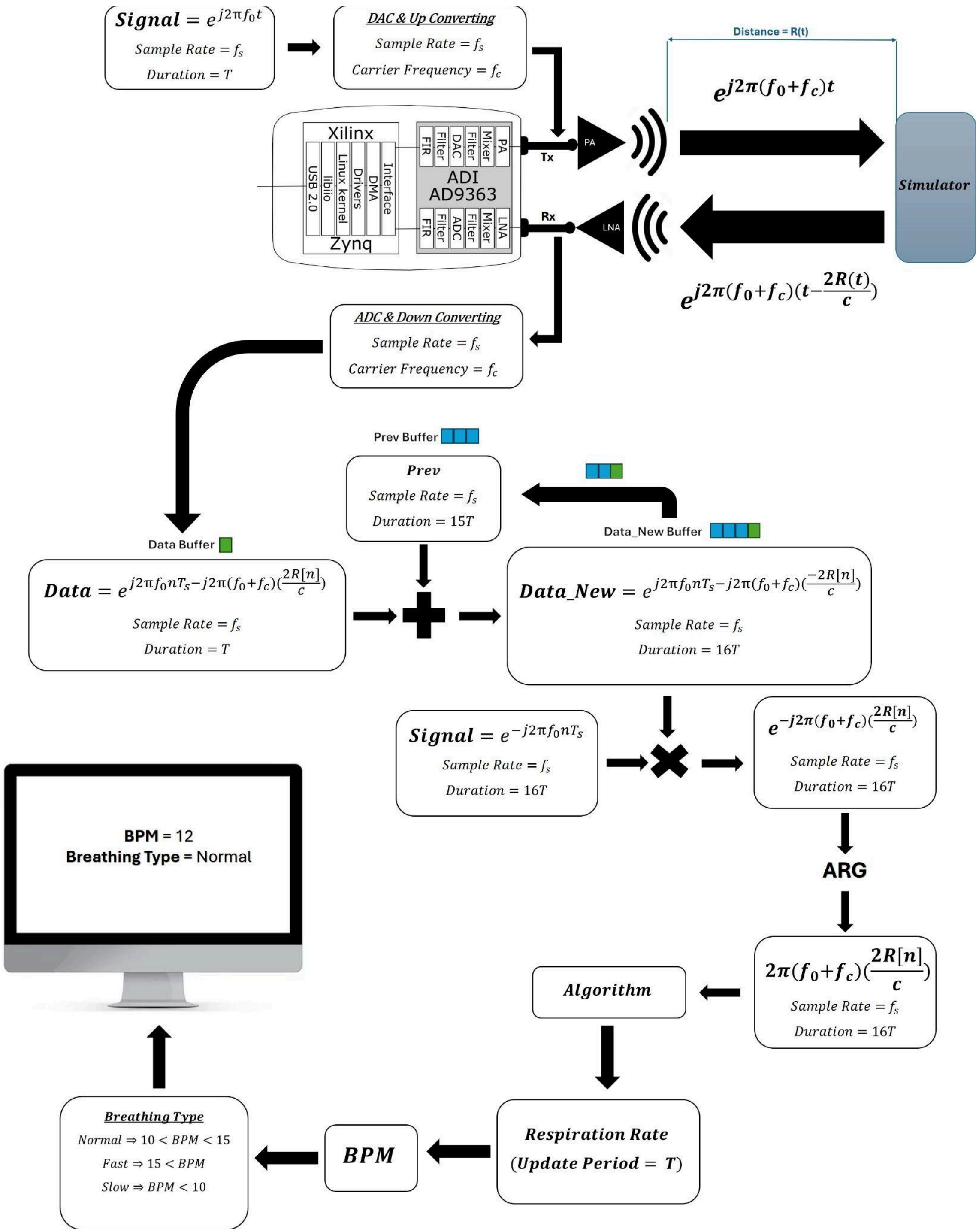

Figure 3: *Signal Processing Flowchart*

Principle of Operation

The CW radar-based method is based on finding the amount of displacement by utilizing the phase modulation of the transmitted signal caused by small chest movements associated with respiration. As can be seen from Figure 3, signal processing consists of several steps.

1. Signal Transmission and Reception

A sinusoidal signal at a low frequency F_0 is generated and upconverted to the carrier frequency F_c. The transmitted RF signal is given by: $s(t) = e^{j2\pi(F_0+F_c)t}$.

When the received signal is reflected from the chest, it experiences a delay equal to the time it takes to reach the RX antenna from the TX antenna. This delay causes a phase shift $\tau = \frac{2R(t)}{c}$, corresponding to the displacement $R(t)$ in signal: $As(t - \frac{2R(t)}{c}) = Ae^{j2\pi(F_0+F_c)(t-\tau)}$. So, the received and downconverted signal is given by: $r(t) = Ae^{j2\pi F_0 t - j\Phi(t)}$ where $\Phi(t) = \frac{4\pi(F_0+F_c)R(t)}{c}$ [8].

2. Transmission and Reception Signal Duration Selection

To ensure accurate respiration rate estimation, the duration of the transmitted and received signal must be appropriately selected. The signal receiving & respiration rate update period should be small enough to be considered real-time. For this reason, we set the signal receiving duration as: $T = 2\,sec$.

On the other hand, our respiration rate data should detect very low breathing rates. For this reason, we set the length of the respiration rate detection data as $16T = 32\,sec$.

To do this, we used a template buffer called prev with a size of $15Tf_s$. We added the Tf_s length data we just received to the end of the last $15Tf_s$ samples of the data in the previous while cycle. Then, we updated the previous template buffer with the last $15Tf_s$ sample of the $16Tf_s$ length data we newly obtained.(f_s: sample rate, T_s: sampling period.)

3. Phase Extraction and Unwrapping

To extract respiration-induced phase variations, the received signal is mixed with the conjugate of the transmitted signal to remove the high-frequency carrier component: $y(t) = r(t)e^{-j2\pi F_0 t} = Ae^{-j\Phi(t)}$ (in discrete-time domain $t \rightarrow nT_s$, $\Phi(t) \rightarrow \Phi[n]$.).

Then, the $32T\ sec$ long phase data is unwrapped to obtain a continuous phase trajectory: $\Phi[n] = unwrap(\angle y(t)) = -\frac{4\pi(F_0+F_c)R[n]}{c}$.

The Algorithm

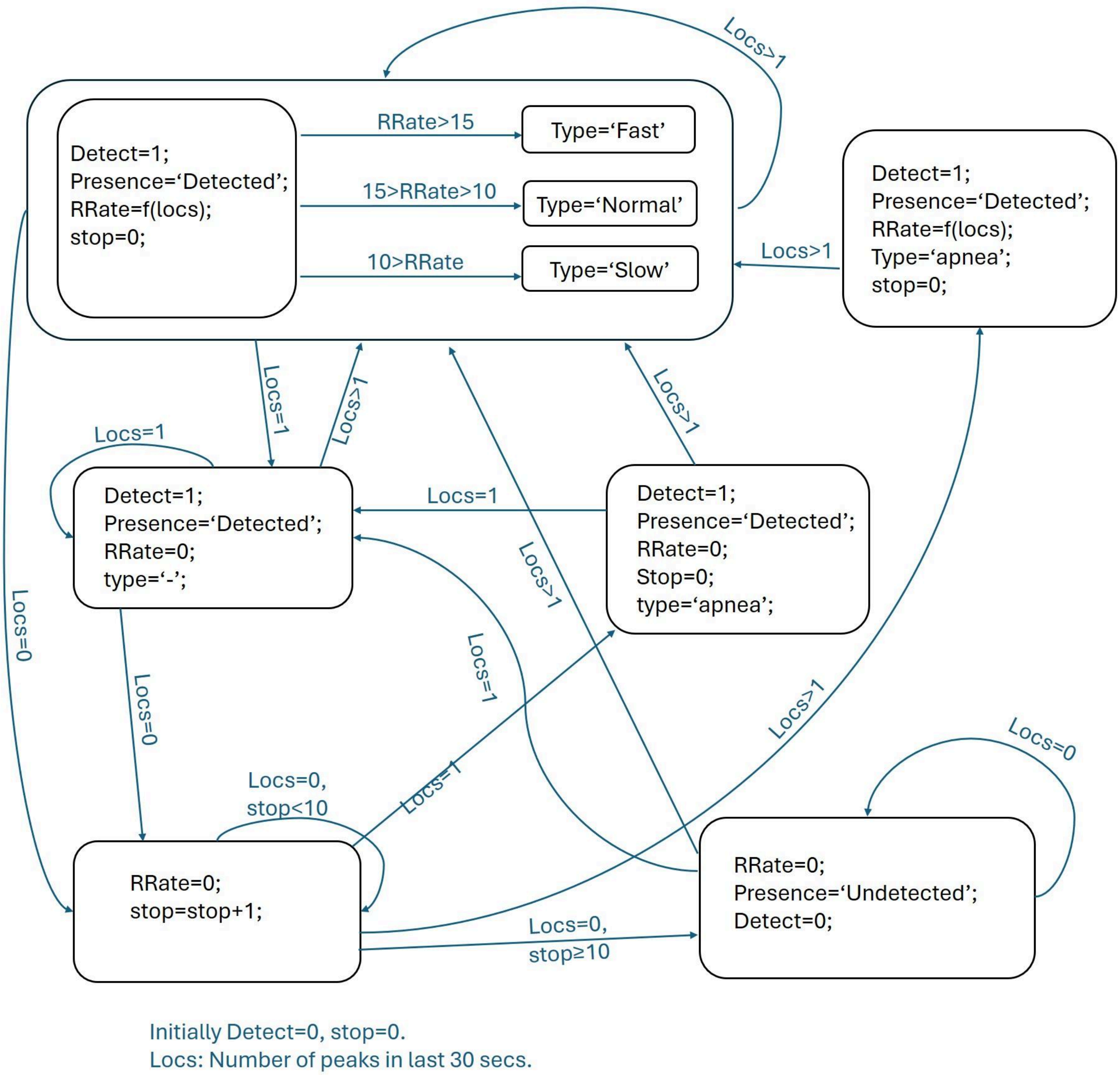

Figure 4: *Classification algorithm flowchart*

1. Envelope Detection and Peak Analysis

To obtain respiration pattern peaks clearly, an envelope detection function extracts the upper phase boundary.

Then, the peak points higher than a certain threshold were found at certain intervals from the output of the envelope function.

Peaks in the upper envelope correspond to inhalation cycles. The time intervals between consecutive peaks: ΔT provide the respiration period, so:

$Respiration\,Rate(\,BPM) = \frac{60}{mean(\Delta T)}$ obtained. (1)

2. Classification of Respiration Patterns

The algorithm detects vital sign presence, breathing mode, and calculates the respiration rate (bpm) by analyzing the number of peaks in the breathing signal within a window of the last 30 seconds. It changes states by checking the number of detected peaks (locs) in this window and the stop counter.

Initially, the algorithm starts from the RRate=0; Presence= "Undetected"; Detect=0; state, while there is no peak yet.

When exactly one peak (locs=1) is found, the algorithm confirms breathing presence (Detect=1) but cannot calculate a reliable breathing rate because at least two peaks are needed for bpm calculation. In this state, the output is "Presence: Detected" ,the respiration rate (RRate) and stop counter is set to zero.

If two or more peaks (locs≥2) are detected, breathing is reliably present. The algorithm resets the stop counter and updates the breathing rate. The presence is set to "Detected," and the breathing mode is classified based on the respiration rate: below 10 bpm as "Slow," above 15 bpm as "Fast," and in between as "Normal."

When the peak or peaks disappear from the 30 sec window (which means Detect=1 from the previous state), the algorithm starts to increment the absence counter (stop) in RRate=0; stop=stop+1; state if peak absence continues. If this counter reaches a threshold (10 consecutive cycles corresponds to stop=10 (20 sec)), the algorithm goes into Rrate=0; Presence= "Undetected"; Detect=0; initial state that declares the presence as "Undetected" and updates the Detect variable to zero. But, if peak/peaks obtained before the absence counter stop reach 10 (1 ≤ stop < 10, in 20 sec), the algorithm labels it as "apnea", which indicates an intermittent absence of breathing. After detection of apnea mode, the algorithm returns to the states when the peak was detected. In this way, if the time elapsed since the last peak is less than 30 seconds, the normal procedure continues; if it is between 30 and 50 seconds, the apnea mode is entered; if it is more than 50 seconds, the undetected mode is entered.

Respiration Rate Calculating Function (f(.) in the figure 5):

To ensure reliable calculation, if the average interval between peaks in the last 30 seconds is smaller than the interval between the time the last peak occurred and the current time, the current time is also used as the peak in the calculation in equation (1).

Simulator

The simulator used to model breathing consists of a linear actuator motor, Arduino Uno, display screen, motor driver, buttons, 12V power supply, and agar mixture. The linear actuator is the LA-M-12-120 12V 30mm 96N IP54 Micro Linear Motor model, and an L298N motor driver drives this motor. This linear actuator was chosen because it has a force of 96 N and a speed of 9.5 mm/s at full load [9]. Arduino Uno controls the motor driver. The simulator has 3 modes for breathing types. These are normal breathing, fast breathing, and apnoea. All 3 modes are managed with switches. Breathing modes are as follows:

Fast breathing: 20 BPM

Normal breathing: 12 BPM

Apnoea breathing: 20 seconds of breathing and 40 seconds of breathlessness

The code to control this is embedded in Arduino Uno. According to the incoming command, the agar mixture at the end of the linear actuator will move back and forth at the appropriate frequency. The simulator's mode will be shown on the Nokia 5110 LCD screen. There are some points to consider when preparing the agar mixture. Since the transmitted signal is 4.6 GHz, human permittivity is approximately 52-55 in an average person (varies depending on fat content). To obtain this permittivity, a mixture of agar, water, and salt will be used.

The proportions required for the mixture are approximately as follows:

Water: 98.2%

Agar: 0.8%

Salt (NaCl): 1%

The agar-based phantom was prepared by boiling the mixture, casting it into a mold, and allowing it to solidify. It was then mounted onto the 3D-printed platform positioned at the end of the simulator. Simulator connections can be seen in Figure 5.

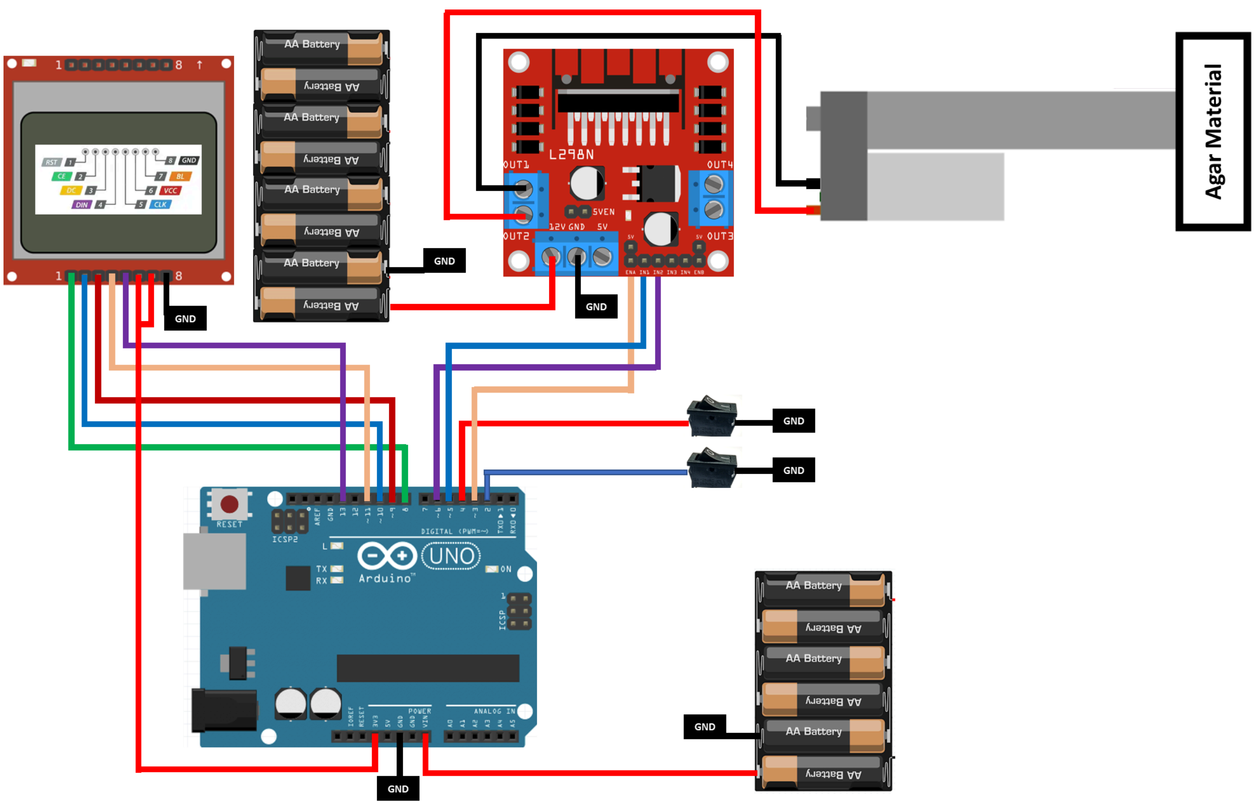

Figure 5: *Respiration Simulator Connections*

User Interface

The User Interface Unit provides direct interaction between the user and the system, allowing easy understanding and use of the system both visually and in terms of control. Developed as an executable application (.mlapp), the UI was implemented on a personal computer and interfaces directly with signal processing algorithms running in MATLAB. Upon initialization, the UI allows the user to start and stop data acquisition, monitor live respiratory activity, and view key outputs such as breaths per minute (BPM), presence detection, and breathing mode classification (normal, fast, or apnoea). The graphical output includes a real-time plot of the unwrapped phase signal, with inhalation peaks marked to support interpretability. The UI updates its graph directly according to the incoming RF signal and we can see the results clearly on our screen. The interface, which we aim for a simple use, can be operated by even non-technical users with minimum information. This increases efficiency in clinical or field use.

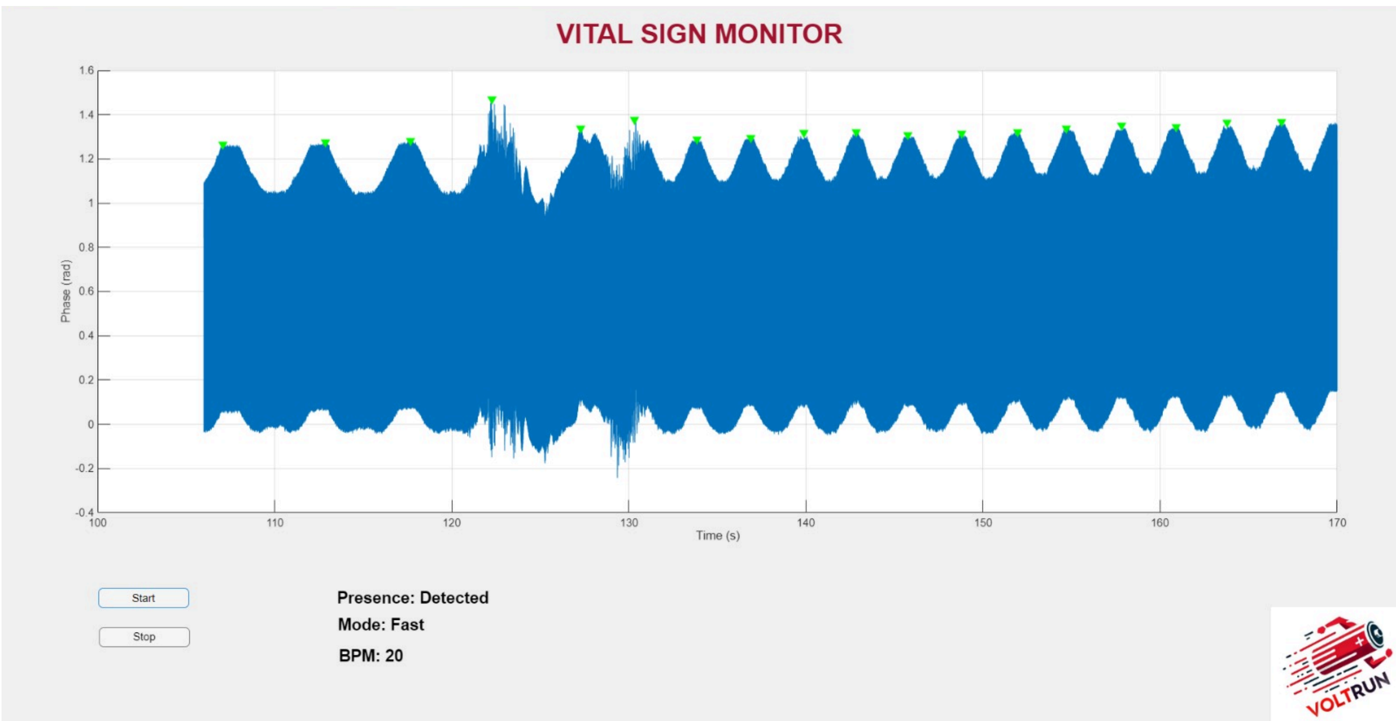

Figure 6: *User Interface Example*

Test Results

Various controlled tests were conducted to test the system requirements. As a result of the tests, the ability of a Software Defined Radio (SDR) based radar system to detect and classify vital signs movements was successfully demonstrated. The test system, which used Adalm Pluto SDR and 4.6 GHz patch antennas, was able to reliably track simulated respiratory movements under various controlled conditions. The tests were conducted in a carefully selected test environment to increase the reliability of the data.

Three main tests were performed: movement detection, respiration rate (BPM) detection, and breathing mode classification. In all tests, the simulator's (agar solution part) distance from the patch antennas was varied between 50 cm and 200 cm. The results consistently showed high detection accuracy across all distances, with error margins well below the 20% threshold defined as acceptable for the system.

The system detected chest movement in a worst-case scenario in a 2m × 2m area within 130 seconds. The area scan was performed by swiping from one side at 10-second intervals and repeated every 20 cm, which is the width of the agar solution used in the simulator. This process, which lasts 100 seconds, takes place after a 30-second stabilization. It successfully detected the presence of a living being, calculated the respiratory rate, and classified the respiratory mode (normal, fast, or apnea) according to the BPM values.

Based on the test results, it has been confirmed that all system requirements have been successfully met. The system is capable of detecting a living individual within an enclosed space, calculating the breaths per minute (BPM), and classifying the breathing mode. Detailed test data and results can be found in the appendix.

Power Analysis

In the project, two separate units consume power.

SDR Unit

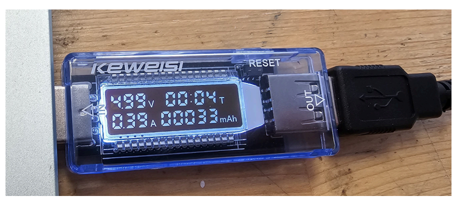

Figure 7: SDR Unit power measurement

Figure 7 shows the power measurement device that is measuring power transferred to the SDR unit under testing operations. It was observed that the SDR unit operates at a supply voltage of 5 volts (DC), drawing currents ranging between 0.39 and 0.41 amperes under active operational conditions. When the SDR unit is connected to the computer but not actively operating, it draws a constant current of approximately 0.37 amperes at 5 volts. Consequently, the SDR unit exhibits power consumption levels between 195 and 210 milliwatts during active operation and approximately 185 milliwatts in standby mode [9].

Simulator Unit

It delivers a mechanical force of 96N with a speed of 9.5mm/s. The mechanical power delivered is:

Power(W) = Force (N) x Speed (m/s)

It delivers a mechanical power of 912 mW. The type of actuator that we use usually operates at 80% efficiency. Therefore, the actual power needed to operate the simulator unit is:

0.912 / 0.8 = **1.3 Watts**

Cost Analysis

You can see the expenses during the development process of the system in Table 2.

Table 2: *Cost Analysis of Development Process*

Component	**Description**	**Approx. Cost**
Engineering and Development Costs	Costs associated with the time and expertise of engineers involved in system design, development, testing, and integration	$40
Material & Component Costs	Expenses for electronic components, structural materials, and consumables required for assembling and operating the system	$250
Manufacturing & Fabrication	Costs incurred during the fabrication of custom parts, such as 3D printing and mechanical assembly	$50
Total		**$340**

You can see the expenses of the final product in Table 3.

Table 3: *Cost Analysis of Final Product*

Component	**Description**	**Approx. Cost**
ADALM-PLUTO and Antennas	Software-defined radio platform, Patch Antennas	$100
Matlab	Open-source DSP software	$0
Motor Driver	L298N Multi-Channel Motor Driver	$2
Linear Actuator	The motor that converts rotary motion into linear motion for the respiration simulator	$40
Microcontroller	Arduino Uno for simulator control	$10
Display Screen	Nokia 5110 LCD Screen	$5
3D-Printed parts	Simulator Agar-Holder Platform	$40
Simulator Box	Box Containing Simulator Parts	$15
Miscellaneous Components	Cables, connectors, agar powder, and batteries	$20
Total		**$232**

Deliverables

1. Vital Sign Monitoring System

The vital sign monitoring system is the main part of this project, which consists of ADALM-PLUTO SDR as the primary radar module, a signal processing structure (developed using MATLAB), and an antenna designed to operate at 4.6 GHz. The system is capable of detecting motion frequencies corresponding to respiration rates, classifying breathing patterns, and operating effectively behind opaque barriers.

2. Mechanical Respiration Simulator

The mechanical respiration simulator replicates human chest movement during breathing to test and validate the radar system's accuracy. It can generate three distinct breathing patterns: normal, fast, and apnea.

3. Documentation

Documentation includes technical reports, test results, and a user manual. The user manual can be accessed from Appendix 2. The technical reports detail the design process, system architecture, and signal processing algorithms used in the radar system. Test plans and results outline the performance metrics achieved during validation, including accuracy, error rates, and system reliability. The user manual provides clear instructions about system setup, operation, and troubleshooting.

4. Source Code

The project deliverables include the complete source code for the radar system, implemented using MATLAB. This includes flowgraphs, scripts, and algorithms for signal processing, frequency detection, and breathing pattern classification. By providing open and accessible source code, this deliverable ensures that the system can be continuously improved and adapted to new use cases.

Conclusion

The VOLTRUN Contactless Vital Sign Monitor is a product of a multidisciplinary engineering project aimed at developing a non-invasive, reliable, and autonomous way to monitor vital signs and breathing patterns for living beings. The system is intended for use in environments where traditional monitoring methods are either unsafe or impractical, such as military zones, infectious hospital wards, and disaster response areas.

The core objective of the project was to build a radar-based system that can detect human presence and monitor breathing without requiring physical contact or a direct line of sight. It operates effectively within a closed space measuring 2 meters by 2 meters and meets key conditions related to cost, power consumption, usability, and real-time operation.

The system includes several integrated components that work together to achieve its functionality. Base equipment is a software-defined radio platform that transmits and receives continuous radar signals using directional antennas. These signals reflect from the living being's movements, and significant changes in the returned signal are used to detect breathing patterns. The signal processing unit then analyzes this data to calculate the number of breaths per minute and classify the breathing mode as normal, fast, or apnea. The processing chain is designed to handle interference from noise, signal drift, and surrounding objects, ensuring reliable performance.

A mechanical simulator was developed to replicate realistic breathing motions to support testing and validation. This simulator uses a motor-controlled actuator and an agar-based material that imitates the electromagnetic properties of human tissue. It allows for repeatable testing of the radar system under different conditions.

A graphical interface was also developed to allow users to operate the system, start and stop scans, view real-time data, and receive automatic feedback on breathing activity. The interface is designed to be intuitive and clear, making the system suitable for use by both technical and non-technical users without requiring special training.

The system was tested in different controlled environments, including tests involving obstacles, different distances, and simulated breathing patterns. Results showed that the device could accurately detect presence and measure breathing rate with less than 10% error. Breathing mode classification accuracy was above 90%, and the mechanical simulator performed within its expected range.

In conclusion, the VOLTRUN system is ready for real-world use. It offers a strong platform for future development, including larger detection areas, multi-person tracking, and AI-based analysis. This makes it a valuable contribution to the fields of remote healthcare, emergency services, and non-intrusive sensing technologies.

Discussions

Safety Considerations

Our non-contact vital function measurement system offers minimal safety risk under standard operating conditions. It does not pose any electrical damage hazards because it uses low-power radio frequency (RF) waves and does not require physical contact. In addition, low-voltage power supplies are used. Proper antenna alignment and shielding measures were taken into account during the design to prevent unwanted exposure or signal interference. The mechanical parts used in the simulator are not sharp or fragmenting and do not operate at high speeds. In addition, the agar used is biologically safe. As a result, our system does not pose a problem for human health.

Societal Impact and Application Potential

This system has the potential to positively impact society, especially in healthcare, emergency response, and military fields. It can be used for continuous, contactless patient monitoring in hospitals, intensive care units, or during sleep studies. In crisis scenarios such as earthquakes, the device can help find survivors trapped under debris, increasing rescue success rates. We believe it will be useful in detecting terrorist elements in military operations. Furthermore, the developed algorithms (particularly phase shift analysis for respiratory detection) can be used for smart home healthcare systems, elderly care, or even automotive security monitoring. As a low-cost, camera-free system, it has the potential for scalable deployment in underserved or resource-limited areas, providing greater access to vital signs monitoring technology.

Environmental Considerations

The system consists of a compact design with minimum electronic components. Since it is made by directly programming the SDR, it can be reprogrammed and allows for further developments using minimum resource consumption. In addition, the power consumption is quite low, both the SDR and the simulator operate safely under 2.5W. The agar we use in the simulator is degradable and harmless to nature. In addition, since it is a camera-free system, it is not dependent on rare and expensive materials used in camera production. In general, our system does not pose a serious risk to the environment.

Appendix 1: Performance Tests

Test Procedure Of the Simulator

1. The mechanical setup was placed on a stable platform (an empty desk) to minimize vibrations. Smooth linear motion ensured on a stable platform. The distance covered by the linear actuator during its horizontal movement in the simulator was measured using a ruler. The reflective object (agar solution) was attached to the moving mechanism.
2. When performing each test case, the system will be calibrated with a chronometer to check BPM correction for each measurement.
3. Oscillation is performed at 3 different breathing modes controlled with Arduino. The distance of the simulator to Adalm Pluto and the BPM of the moving object were adjusted separately for each test.

Test 1: Vital Sign Test

Test Procedure Of Vital Sign Test

1. Start by setting up the test environment described in the previous related parts.
The SDR module is aligned with the motion path.

2. Continue by setting up the test module and configuring the SDR.
The antennas are connected to the Adalm Pluto, which is then connected to the PC through a USB cable. Adalm Pluto SDR and 4.6 GHz tuned patch antennas are configured to transmit a continuous wave (CW) signal at 4.6 GHz. Algorithms implemented on MATLAB detect motion.

3. The next step is the detection.
The test cases are Simulator ON and OFF. For each case, the distance of the simulator to Adalm Pluto is increased 3 times, starting from 50 cm with a 50 cm increasing step size until 200 cm. The movement that occurs when the simulator is placed in a 2m x 2m area is open, and the inactivity that occurs when the simulator is closed is detected and displayed on the user interface.

4. As the last step, validate the data.
Radar-detected data were compared with ground truth values, and percentage errors were calculated for each measurement. We achieved a margin of error below 20%, which was our goal for our design.

Test Parameters of Vital Sign Test

Table 4: *Test parameters of Vital Sign Test*

Parameter	Range	Step Size	Number of Measurements
Simulator’s distance from the sensing device	50 cm to 200 cm	50 cm	5
Movement in the closed area	Simulator ON, Simulator OFF	-	5

Our Vital Sign Test parameters for the vital sign test can be seen in Table 4. As can be seen, we change the distance of the simulator from the SDR and the movement within the closed area once in each step.

We selected the test parameters considering the following conditions:

- We are trying to detect movement in a closed area because we want to test the accuracy of our detection algorithm.
- We change the object’s distance from the sensing device at different distances because we wanted to test the accuracy of our vital sign detection algorithm depending on the distance between the simulator and the patch antennas.

Test Data of Vital Sign Test

Table 5 shows the test values recorded for each scenario described in the test procedure.

Table 5: *Testing the movement from the simulator working and the inactivity resulting from its not working in 50 cm steps from 50 to 200 cm. At each step, the detection period is also measured.*

Vital Sign Test				
	Simulator OFF		**Simulator ON**	
	Detection	**Detection Period**	**Detection**	**Detection Period**
50 cm	YES	30 sec	YES	30 sec
100 cm	YES	30 sec	YES	30 sec
150 cm	YES	30 sec	YES	30 sec
200 cm	YES	30 sec	YES	30 sec

Test 2: BPM Detection Test

Test Procedure Of BPM Detection Test

1. Start by setting up the test environment as described in the previous related parts.
The SDR module is aligned with the motion path.

2. Continue by setting up the test module and configuring the SDR.
The antennas are connected to the Adalm Pluto, which is then connected to the PC through a USB cable. Adalm Pluto SDR and 4.6 GHz tuned patch antennas are configured to transmit a continuous wave (CW) signal at 4.6 GHz. Algorithms implemented on MATLAB detect BPM.

3. The next step is the detection.
The test cases are 12 BPM and 20 BPM. For each case, the distance of the simulator to Adalm Pluto is increased 3 times, starting from 50 cm with a 50 cm increasing step size until 200 cm. The BPM value created by the simulator placed in a 2m x 2m area is detected and displayed on the user interface.

4. As the last step, validate the data.
Radar-detected data were compared with ground truth values, and percentage errors were calculated for each measurement. We achieved a margin of error below 20%, which was our goal for our design.

Test Parameters of BPM Detection Test

Table 6: *Test parameters of BPM Detection Test*

Parameter	Range	Step Size	Number of Measurements
Simulator’s distance from the sensing device	50 cm to 200 cm	50 cm	5
Simulator’s BPM	12 BPM and 20 BPM	8 BPM	5

Our BPM Detection Test parameters for the BPM Detection Test can be seen in Table 6. As can be seen, we change the distance of the simulator from the SDR and the BPM of the simulator once in each step.

We selected the test parameters considering the following conditions:

- We are trying different values of the simulator’s frequency (BPM) because we want to test the accuracy of our measurements depending on BPM.
- We change the object’s distance from the sensing device at different distances because we wanted to test the accuracy of our BPM detection algorithm depending on the distance between the simulator and the patch antennas.

Test Data of BPM Detection Test

Table 7 shows the test values recorded for each scenario described in the test procedure.

Table 7: *The simulator was set to 12-20 BPM, and measurements were taken for each BPM value starting from 50 cm to 200 cm with a 50 cm step size. It was compared whether the measurements were compatible with the simulator's BPM. At each step, the detection period is also measured.*

Vital Sign Monitor Simulator Test						
BPM	**12 BPM**			**20 BPM**		
	Detected Value	**Error Value**	**Detection Period**	**Detected Value**	**Error Value**	**Detection Period**
50 cm	11-13 BPM	8.3%	40 sec	19-21 BPM	5%	36 sec
100 cm	11-13 BPM	8.3%	40 sec	19-21 BPM	5%	36 sec
150 cm	11-13 BPM	8.3%	40 sec	19-21 BPM	5%	36 sec
200 cm	11-13 BPM	8.3%	40 sec	19-21 BPM	5%	36 sec

Test 3: Breathing Mode Classification Test

Test Procedure Of BPM Detection Test

1. Start by setting up the test environment as described in the previous related parts.
The SDR module is aligned with the motion path.

2. Continue by setting up the test module and configuring the SDR.
The antennas are connected to the Adalm Pluto, which is then connected to the PC through a USB cable. Adalm Pluto SDR and 4.6 GHz tuned patch antennas are configured to transmit a continuous wave (CW) signal at 4.6 GHz. Algorithms implemented on MATLAB detect the Breathing Mode.

3. The next step is the detection.
For each case, the distance of the simulator to Adalm Pluto is increased 3 times, starting from 50 cm with a 50 cm increasing step size until 200 cm. The BPM value created by the simulator is detected and displayed on the user interface.

4. The next step is the classification.
Test cases are apnoea, normal breathing, and fast breathing. For each case, the breathing mode produced by the simulator is detected and displayed in the user interface.

5. As the last step, validate the data.
Radar-detected data were compared with ground truth values for each measurement.

Test Parameters of Breathing Mode Classification Test

Table 8: *Test parameters of Breathing Mode Classification Test*

Parameter	Range	Step Size	Number of Measurements
Simulator’s distance from the sensing device	50 cm to 200 cm	50 cm	5
Breathing Mode	Apnoea, Normal and Fast	-	5

Our Breathing Mode Classification Test parameters can be seen in Table 8. As can be seen, we vary the simulator’s distance from SDR and breathing mode, one at each step.

We selected the test parameters considering the following conditions:

- We are trying different breathing modes to test the accuracy of our breathing mode detection algorithm, depending on the simulator’s mode.
- We change the object’s distance from the sensing device at different distances because we wanted to test whether the accuracy of our measurements varies depending on the distance between the simulator and the patch antennas.

Test Data of Breathing Mode Classification Test

Table 9 shows the test values recorded for each scenario described in the test procedure.

Table 9: *Testing the detection algorithm of different breathing modes of the simulator in 50 cm steps from 50 to 200 cm. At each step, the detection period is also measured.*

Breathing Mode Classification Test						
	Apnoea		**Normal Breathing**		**Fast Breathing**	
	Detection	**Detection Period**	**Detection**	**Detection Period**	**Detection**	**Detection Period**
50 cm	YES	50 sec	YES	40 sec	YES	36 sec
100 cm	YES	50 sec	YES	40 sec	YES	36 sec
150 cm	YES	50 sec	YES	40 sec	YES	36 sec
200 cm	YES	50 sec	YES	40 sec	YES	36 sec

Appendix 2: User Manual

Contactless Vital Sign Monitor
VOLTRUN Company – Version 1.0

1. System Components

The system consists of the following hardware and software components:

- **ADALM-PLUTO SDR**
- **Patch Antennas**
- **Mechanical Respiration Simulator**
    - Linear actuator
    - Agar phantom
    - Arduino Uno
    - L298N Motor Driver
    - Nokia 5110 LCD Screen
    - 2-bit mode selector (2 buttons)
    - Main simulator power switch
- **PC with executable GUI (.mlapp)**
- **USB cable**

2. Setup Instructions

2.1 Hardware Setup

1. Place the simulator in a 2m × 2m enclosed test area, with the SDR antennas outside and on the same side as the user.
2. Connect patch antennas to the TX and RX ports on the ADALM-PLUTO SDR.
3. Connect the SDR to the PC via USB.
4. Set the simulator power switch and adjust the switch according to the breathing mode.

2.2 Software Setup

1. On the PC, launch the **VITAL SIGN MONITOR .mlapp application**.
2. Verify that the plot area loads and the **Start** and **Stop** buttons appear.
3. Click **Start** to begin real-time data acquisition and signal processing.

3. Operating the Simulator

3.1 Powering On

- Turn ON the **main simulator switch** to activate the simulator circuit.
- The LCD screen should light up and display the breathing mode.

3.2 Selecting Breathing Mode

The simulator has 2 physical mode switches (binary encoded) to choose among 3 breathing types:

Table 10: Configuration of *Simulator Mode-Switches*

Button 1	**Button 2**	**Mode**
0	0	Simulator OFF
0	1	Fast Breathing
1	0	Normal Breathing
1	1	Apnoea

Modes can be changed in real time; changes are reflected on the LCD and detected in the GUI.

- Fast breathing: 20 BPM
- Normal breathing: 12 BPM
- Apnoea: Prolonged breathlessness after breath detection

4. Understanding the User Interface

After clicking **Start**, the following elements appear on the GUI:

- **Live Phase Plot** – Shows phase data over time (example in image).
- **Green Triangles** – Detected inhalation peaks (used for BPM calculation).
- **Presence Status** – Shows whether a living object is detected. (Detected / Undetected)
- **Mode** – Automatically determined as Apnoea / Slow / Normal / Fast.
- **BPM** – Detected breaths per minute.

Sample Display:

```
Presence: Detected

Mode: Fast

BPM: 20
```

5. Troubleshooting

Issue	Possible Cause	Solution
No GUI output	SDR is not connected properly	Reconnect the USB, relaunch the .mlapp
The phase signal is flat	Simulator switch is OFF	Turn ON the main switch
The mode doesn't change in the GUI	Button input not recognized	Verify button wiring, press firmly
BPM not shown	Weak signal / wrong distance	Keep within a 50–200 cm range
Wrong Mode displayed	Agar is not moving as expected	Check the actuator and button logic

6. Maintenance and Safety Notes

- The simulator is battery-operated. The battery should be replaced at regular intervals.
- Do not touch moving parts during operation.
- Replace agar phantom every 2–3 weeks or when dried.
- Keep the system away from direct moisture or extreme heat.

7. Technical Support

📧 **teamvoltrun@gmail.com**

8. Version Information

- **System Version:** 1.0
- **Interface Type:** Windows Executable (.mlapp)
- **Simulator Control:** Physical switches + main switch
- **Last Update:** 25.05.2025

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