

Radar-Based Vital Sign Monitoring with Automated Beam Steering

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Abstract

Hospitals monitor an infant's vital signs after birth to quantify the status of its body during incubation. This is often done by adhesively connecting biometric devices to every infant in the hospital nursery. However, if the need for physical connections were to be eliminated and a single device is used to monitor every incubator, infants can experience increased comfort and vital sign monitoring costs largely decrease. To solve this problem, a team of five undergraduate students participated in an ongoing research project that is developing a wireless multitargeted vital sign monitor (VSM), and as their capstone design project developed hardware that automated the VSM deployment. This paper discusses the automated VSM design, along with educational outcomes for the students. The team's project relies on a double phase shifter (DPS) phased array to repeatedly steer a radio frequency (RF) beam between desired targets to gather their vitals wirelessly. A plain phased array could be used in this context; however, its ability to target a beam at a precise location is limited. Equipping the antenna array with DPS produces a highly focused beam that can localize closely spaced targets. After targeting the beam, a receiver records the infant's heart rate and breathing rate. To automate the beam design process, a programmable controller was implemented to drive the control voltages at each phase shifter. Doing this causes a shift in the beam's direction, which depends on the location of a target and unwanted neighboring targets. Finally, using fast Fourier transforms (FFTs), the frequency information of the infant's vitals is recovered. To test the system's effectiveness, an experiment was conducted on two human targets. The device successfully recovered each target's vital signs, which demonstrates its promising applications in medicine.

1. Introduction

Hospital nurseries commonly monitor infant vital signs by connecting biometric monitors to newborns

through their incubators. While this procedure produces accurate readings, the hardware setup is costly and potentially uncomfortable for the newborn. Cost issues become a visible concern if one sums the prices of all the biometric monitors in an incubator and multiplies the result by the total number of incubators in a hospital nursery. Typically, the net expense can surpass tens or hundreds of thousands of dollars, depending on the size of the nursery (Tarus 2023).

When considering other issues, including incubator sensors breaking over time and needing to be replaced, and the issue of newborns experiencing discomfort from the sensors surrounding their body, clearly the efficiency of many infant VSMs can be improved (Rajalakshmi 2019). Therefore, instead of putting a collection of costly sensors in a large array of incubators, a cost-friendly approach would be to have one wireless device that scans infants individually and provides a corresponding health report. Such a device would eliminate the potential issues associated with wired monitors, as well as costs due to installation, continuous electronic servicing, and occasional replacement. To develop such a device, a team of five undergraduate students at Rutgers University leveraged remote sensing using radar (Xu 2023; Li 2009) for their capstone design project.

In the context of radar-based sensing, the team relied on phased array technology (Jeffrey 2009). Phased arrays are multi-element antennas that can steer beams of RF energy in different directions (Mailloux 2018). Depending on the application, beams generated by a phased array can be used as an adjustable channel to transmit information to any target inside of it. For example, if a transmitter wanted to send a message to three receivers, and the locations of those three receivers are known to the transmitter, then the transmitter could sequentially steer the beam to the three receivers and individually send them a message. However, this works under the assumption that the receivers are spaced far apart from each other. In the situation where targets are closely spaced together, the beam can overlap across multiple targets, making one-on-one communica-

tion between the transmitter and receiver difficult to isolate (Xu 2022).

For the purposes of a nursery, it can be assumed that incubators are spaced close together due to indoor capacity requirements for hospitals (Humphreys 2022). As a result, a highly focused beam must be generated to ensure stable communication between infants and the transmitter. Many plain phased arrays are unable to accommodate such a requirement, which drives the need for a new technological implementation. To combat this problem, the team turned to double phase shifter (DPS) technology.

Typically, phased arrays have one phase shifter per antenna element to steer the beam. The transmitter can preset the phase at each phase shifter to pull the beam in a certain direction, while also distributing power within the beam, suppressing its side lobes (Stoica 2015). For targets that are far apart from each other, one phase shifter per antenna is enough to establish isolated communication between one transmitter and one target. However, since multiple targets are spaced closely together in a nursery setting, the power distribution in the beam should be condensed into a narrow region. This is where DPS comes in: by adding two phase shifters at each antenna, the distribution of power within the beam becomes much narrower. As a result, a single target in the main beam will be localized, while neighboring targets are suppressed to nullify undesired interference (Stuckman 1990; Vouras 2011). Figure 1 exemplifies this process, where one-on-one communication is easier to achieve among closely spaced targets.

To adopt this technology into an infant monitoring system, multiple contributions were necessary. Firstly, with the help of Dr. Michael Wu's group at Rutgers University, the team was able to integrate a custom 4-element DPS phased array into the system design (Xu 2024). Then, using a DPS algorithm developed by Xu (2023), custom circuitry and software was designed to control the two-phase shifters at each antenna element of the DPS phased array.

The system design of the multitargeted VSM is explained in section 2 of this paper, where aspects of hardware

and software development, experimental results, and costs are discussed in detail. Section 3 highlights the educational outcomes for the team members after completing the project. Finally, section 4 discusses the overall sensibility of the monitoring system and its future direction for future capstone projects.

2. Methods and Results

The objective of the team's capstone project is to create a remote infant monitoring system by automating the beam steering capabilities of DPS. To complete the design, numerous hardware and software considerations needed to be made. In this project, two main questions regarding hardware were scrutinized. First, what kind of controller can be used to steer the beam? Since the phased array has 8 analog phase shifters, the controller must efficiently convert digital commands into analog voltages. Second, what kind of driver circuitry is required between the controller and the phase shifters? Most controllers nowadays operate on 5V or less, which is problematic because the phase shifters being used in the DPS phased array require control voltages up to 15V.

At the software level, another two questions are left to be explored regarding the signal processing back end of the system. First, how does the phased array know where to steer the beam? To enable beam-

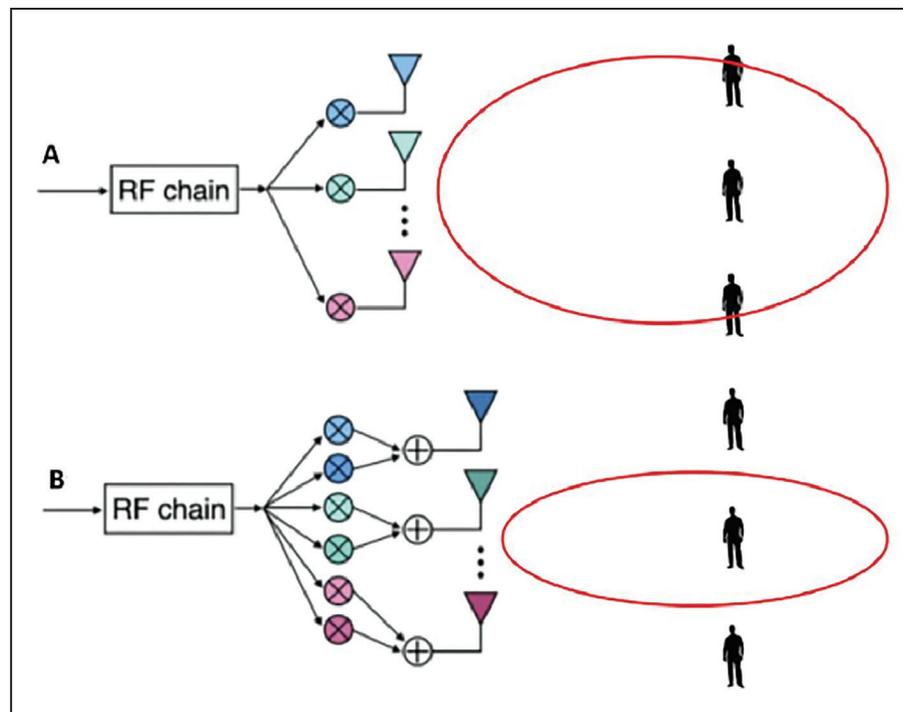


Figure 1. (a) Example beam of a plain phased array on closely spaced targets; (b) example beam of a DPS phased array on closely spaced targets.

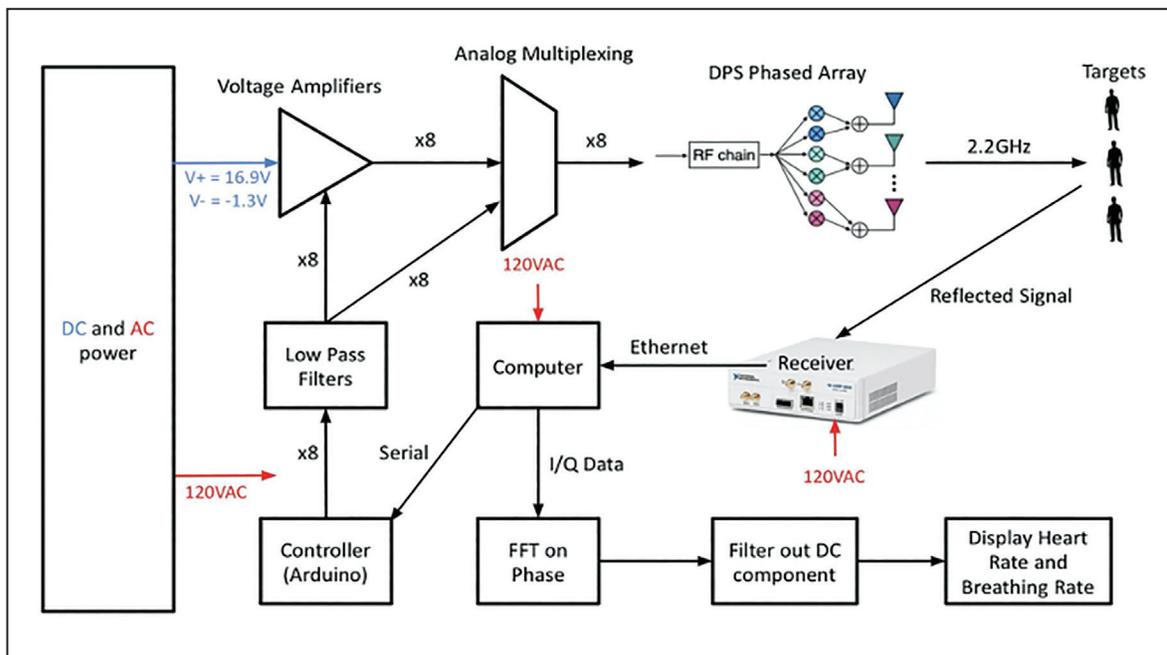


Figure 2. Proposed solution for wireless vital sign monitoring.

forming, the controller must change the DC control voltage at all 8 phase shifters, each of which is meticulously calculated by a DPS optimization algorithm (Xu 2023). Second, how is vital sign information processed? To extract frequency information from received data, a processing algorithm employing the Fourier transform should be implemented.

With these four questions in mind, the team developed the system in Figure 2. The DPS phased array acts as a transmitter, which localizes a target and directs a 2.2GHz pulse at them. The receiver recovers the reflected pulse, which is a modulated 2.2GHz carrier that contains frequency information about mechanical vibrations in the stationary target's body. The recovered data is then sent into a computer, which runs an FFT to recover the frequency components of the echo. Each FFT is expected to contain two peaks: one corresponding to the target's heart rate and one corresponding to the respiration rate. From there, a filtering stage is added to remove any DC components in the data before displaying the vital signs of the corresponding target. Finally, once the vital signs of the first target are recovered, the controller will determine which target to monitor next and steer the beam accordingly. To do this, the controller will send 8 voltages into separate amplifiers, which act as drivers for the individual phase shifters.

The following subsections of this paper scrutinize the subsystems in Figure 2. Section A describes voltage controller design for communication between the computer and the phased array. Section B describes

the receiver used for data recovery of the echo signals. Section C describes the control software that enables beam steering. Section D describes the post-processing software used to extract the respiration rate and heart rate from the receiver. Section E details the results of an experiment conducted with the monitoring system on two human targets. Finally, section F will discuss the costs associated with the prototype.

2.1. Controller and Amplifier Design

To design a voltage controller that would automatically steer the beam by changing eight analog phase shifter voltages (Mini-Circuits 2024) on the phased array, the team designed a system that maps digital inputs to unique analog voltages. At the control port for each phase shifter, a voltage V_{ps} between 0V and 15V can be applied to change the phase of the input. Since most microcontroller outputs V_c can only produce $0V \leq V_c \leq 5V$, an amplifier stage between the controller and phase shifters must be designed to produce a DC voltage gain of at least $15/5 = 3$. Given the constraints of a variable 5V input supply and the required 15V (maximum) output, the system in Figure 3 was implemented. The PWM source is generated by an Arduino Mega. Since the analog output of the Arduino's PWM pins is pulsed with a duty cycle κ , a low pass filter was added to convert the pulsed signal into a DC voltage with a value of 5κ .

After the filter, an amplification stage converts the output range of the PWM pin from 0V-5V to 0V-15V. To do this, an inverting amplifier was designed

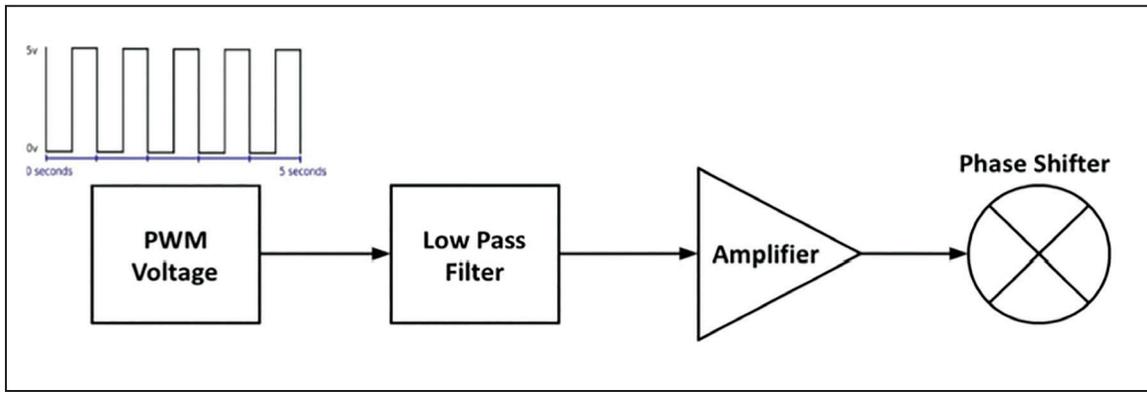


Figure 3. Voltage conversion from PWM to 0V-15V DC.

such that

$$V_{out} = 15 - GV_{in} \quad (1)$$

Where G represents the gain of the amplifier. Given an input of 5k, it follows that

$$V_{ps} = 15 - \frac{5Ga_{in}}{2^N - 1} = 15 - \frac{Ga_{in}}{51} \quad (2)$$

Where $N = 8$ bits and $0 \leq a_{in} \leq 255$ are the PWM settings on the Arduino. Figures 4 and 5 represent the integration of equation 4 into a hardware setup.

The schematic in Figure 4 contains a 1kΩ resistor in parallel with the 3.3nF capacitor, which is a low pass filter. The resulting DC output gets passed into an inverting amplifier with a transfer function like that in equation 1 (Solomon 1974). G is decided by the parallel network of the 1kΩ resistor and the 2.2kΩ feedback resistor, which were tuned to maximize the gain of the amplifier. To check the gain during tuning, the team probed the red dot in Figure 4 and repeatedly produced V_{ps} vs. a_{in} plots, like the one in Figure 5. In the end, the best outcome was:

$$V_{ps} = 15 - 0.0547a_{in} \quad (3)$$

With a 16.9V positive supply and -1.3V negative supply on the LF347 operational amplifier (Texas Instruments 2024). Equation 3 provides the phase shifters with a 1V-15V control range, meaning 0V-1V is not included in the output range. This is due to the output swing of the amplifier being limited to 14V. As a result, a 2-1 analog multiplexer (Analog Devices 2024) was added to the circuit. Since the output range on the filter is 0V-5V, digital control can be used to determine which output must connect to the phase shifter control port. Whenever 1V-15V is required, the MUX will tie the amplifier output to the phase shifter control port; otherwise, the MUX bypasses the amplifier. Note that for most beams, the phase shifters often use voltages higher than 1V, so the MUX component may be optional.

2.2 . Receiver Configuration

After the controller tells the phased array to steer a beam in a unique direction, the signal will reach a stationary target and reflect off it. As a result, the receiver will pick up the vibrations of any moving object inside the beam, namely a beating heart and lungs (Diao 2009). It is imperative for the system to extract these vibrations in the form of frequency information. To do this, the team used a USRP-2920 (National Instruments 2024), which is a software defined radio (SDR) that can transmit and receive data simultaneously. In the context of a radar-based heart monitor, the device gener-

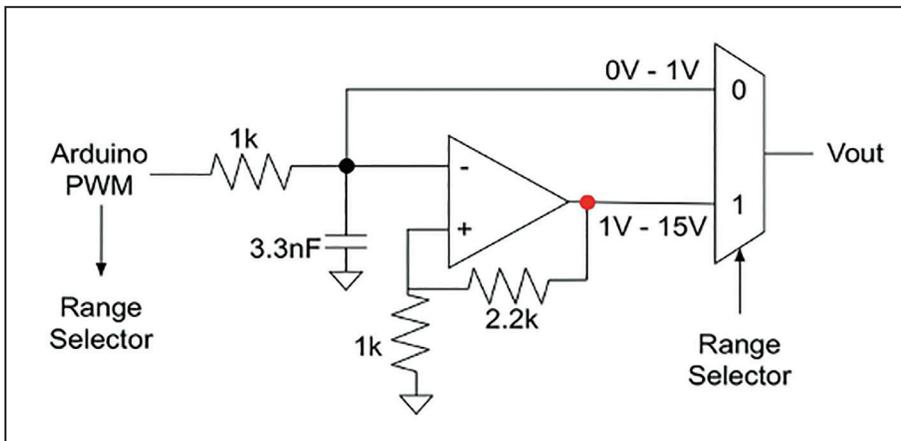


Figure 4. RC filter and amplifier design with range extending multiplexer.

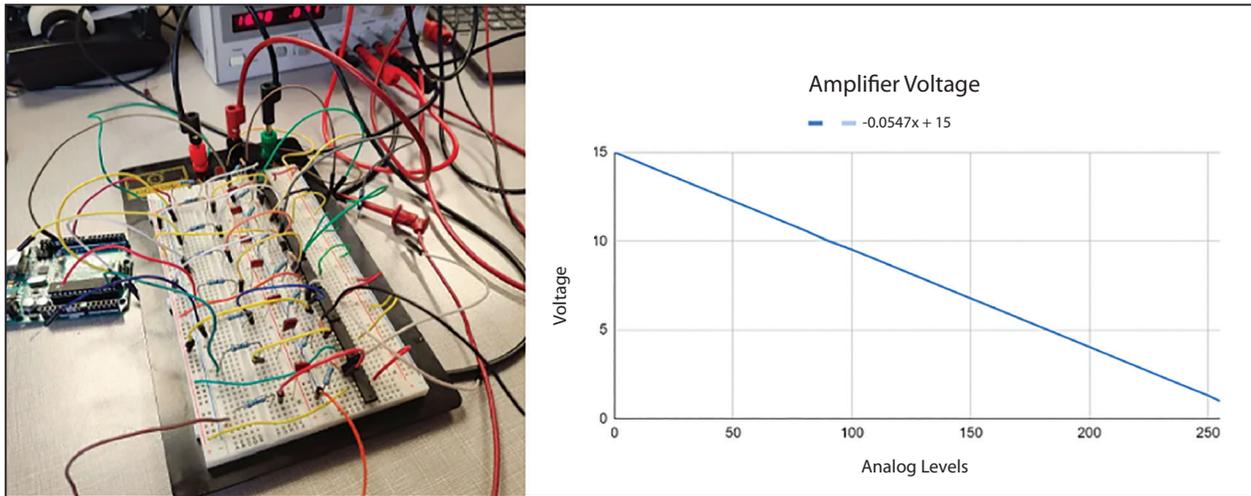


Figure 5. (Left) Implementation of Figure 4 without multiplexers and (Right) Sweep of the output control voltage.

ates a 2.2GHz signal that is passed into the phased array, while also reading echoes caused by the beam encountering a target.

The LabView code uploaded to the USRP consists of two scripts. The first script is used to generate a 2.2GHz signal through the internal RF front end. The second script implemented a real-time receiver, which takes I/Q (real/imaginary signal) recordings of the surrounding environment and exports the data into a csv file. To configure the USRP's I/Q recording outputs for post processing on a computer, several settings in LabView were adjusted. The desired I/Q rate was set to 100,000 samples per second. Since the monitoring time was set to 10 seconds per target for a total of N targets, a recording of one full sweep must be $10N$ seconds and contains $10^6 N$ samples. Finally, the post processing steps in subsection D were taken to extract the breathing rate and heart rate of the desired target.

2.3 . Voltage Control Software

To preset specific analog outputs on the Arduino's PWM pins that feed into the amplifiers, the team found a way to compute each voltage from a set of given input angles (i.e., target locations). To do this, the Arduino must compile the DPS algorithm developed by Xu (2023), which converts a target angle and a set of unwanted neighbors (or nulls) into a voltage vector v with 8 entries. If T represents all the closely spaced targets, the algorithm will run at least $|T|$ times since each target has a unique voltage configuration. For the k -th target in T , the target angle can be defined as T_k and the nulls as $N_k = \{T_z : T_z \neq T_k\}$ where $z=1,2,\dots,|T|$. Therefore, for every k -th target, the corresponding voltage configuration

$v_k = DPS(T_k, N_k)$ where DPS is the DPS algorithm developed by Xu (2023).

Next, the team wanted to introduce automated switching functionality to the phased array by making the code multitargeted. To implement this, the user can enter multiple target angles in an array T . Since the DPS algorithm was originally developed to output one set of voltages, it was modified to output a matrix V^* of voltages. For each k -th target, the k -th row of V^* equals the corresponding voltage configuration $v_k = DPS(T_k, N_k)$.

$$V^* = [v_1, v_2, \dots, v_{|T|}]^T \quad (4)$$

Upon calculating V^* , the eight voltages are loaded into the Arduino as PWM signals and then converted into analog equivalents with the amplifier design in Figure 4. This process is fully depicted in Figure 6, which visualizes the controller implementation across Python and C++. Since the Arduino does not have enough memory to support the computational load of the DPS algorithm, all computations are conducted in Python while control commands are written in C++ and called over Python's "PySerial" library.

2.4. Post Processing Software

After the 2.2GHz echo passes into the receiver, it is processed through the USRP's digital back end and converted into I/Q data. The data is then exported into Excel, which is processed to gather the heart rate and breathing rate of the target. To recover frequency information on the I/Q recordings, it is necessary to analyze the phase θ of the I/Q data $x[n] = I + jQ$.

$$\theta[n] = \tan^{-1}\left(\frac{Q}{I}\right) \quad (5)$$

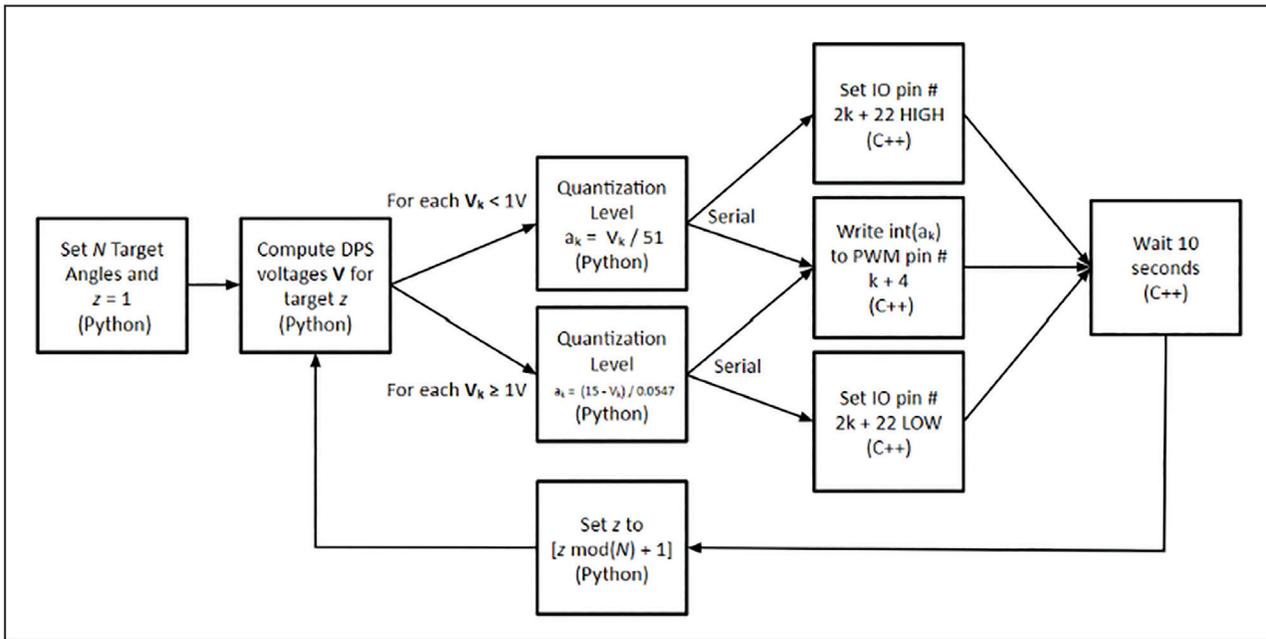


Figure 6. Voltage control algorithm for the hardware depicted in Figure 7.

Since a Doppler shift is formed by the 2.2GHz signal reflecting off the target, the frequency of vibrations in the target's body will be related to the phase of the echoes reflecting into the receiver. Therefore, by using the Fast Fourier Transform (FFT) on $\theta[n]$, the resulting $X[k]$ will contain peaks at frequencies corresponding to the target's heart rate and breathing rate.

$$X[k] = \sum_{n=0}^{N-1} \theta[n] e^{-j2\pi kn} = \sum_{n=0}^{N-1} \tan^{-1}\left(\frac{Q}{I}\right) e^{-j2\pi kn} \quad (6)$$

Where N is the size of the I/Q recording (Patole 2017).

Once the FFT is generated, the Python code will locate the vital sign-related peaks inside the FFT. Since 60bpm=1Hz and the high end of heart rates is about 180bpm, the heart rate peak is expected to be between 1Hz and 3Hz, while respiration rate peaks should be between 0.1Hz and 0.5Hz (Taylor 2022).

Furthermore, the issue of DC components needed to be considered. Since the USRP's I/Q export considers the entire frequency spectrum from 0Hz, a peak at 0Hz is expected due to the 2.2GHz signal having a DC offset. Since the DC component is at a much higher power level relative to the surrounding peaks, any surrounding activity gets suppressed. Therefore, the DC component must be removed by suppressing the magnitude of the peak at 0Hz to the noise floor X_0 , such that $X[k=0Hz] = X_0$.

2.5. Experimental Results

After implementing the system, students conducted a real-time test to assess the viability of the wireless VSM. Figure 7 depicts all the subsystems in Figure 2 being interconnected, which includes the DPS phased array, the receiver/signal generator, a custom voltage controller, power, and a computer for post-processing.

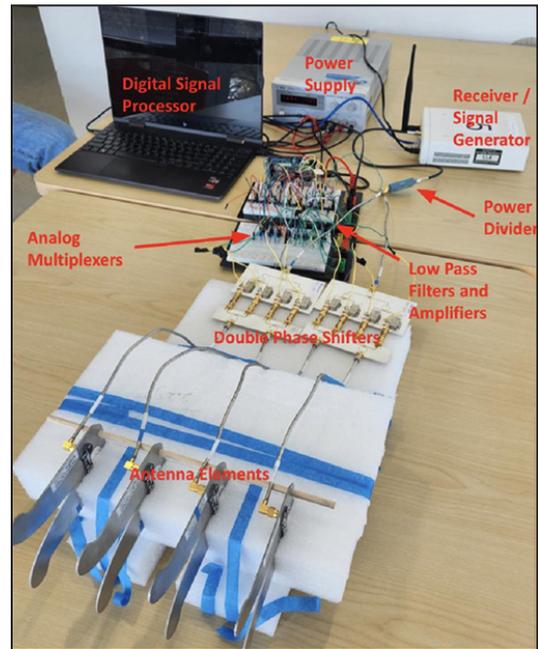


Figure 7. Full vital sign monitoring system.

To assess the system's viability, the test in Figure 8 was conducted (using IRB protocol HRP-503a). Two human targets sat 1.5 meters away from the VSM. One was located 20° off the centerline, while the other target was located at -20°. To steer the beam between targets #1 and #2, the control algorithm in Figure 6 configured the phase shifter voltages to produce the beam patterns in Figure 9. Notice that because of DPS, the sidelobes in both beam patterns are heavily suppressed at the nulls, while the main beams are optimized to nearly 0dB at the targets.

After taking 10 second I/Q recordings of each stationary target and processing the data, the FFT plots in Figure 10 were generated. By analyzing the FFTs, it is estimated that target #1's estimated breathing rate was 0.24Hz or 14.4bpm, while target #2's estimated breathing rate was 0.17Hz or 10.2bpm. Furthermore, target #1's estimated heart rate was 1.28Hz or 77bpm, while target #2's estimated breathing rate was 1.03Hz or 62bpm. Even though clutter is displayed in both plots, the vital signs peaks are noticeably larger, making the vitals relatively easy to see. Note that both targets were instructed to take deep and very slow breaths in an attempt to improve the breathing rate magnitude on the FFT spectrum. These results were calibrated with a smart watch, which can be attached to the target's wrists for monitoring with contact. The system deviated from the smart watch by at most 10% across three total trial runs, which implies that the monitoring system is relatively accurate.

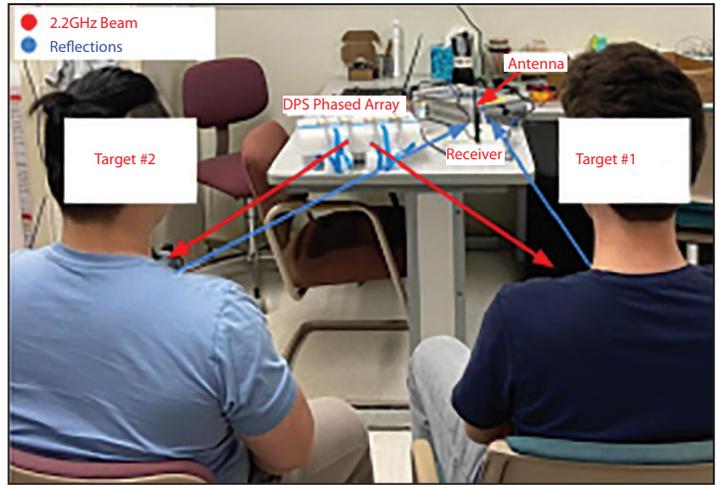


Figure 8. Test on two human targets.

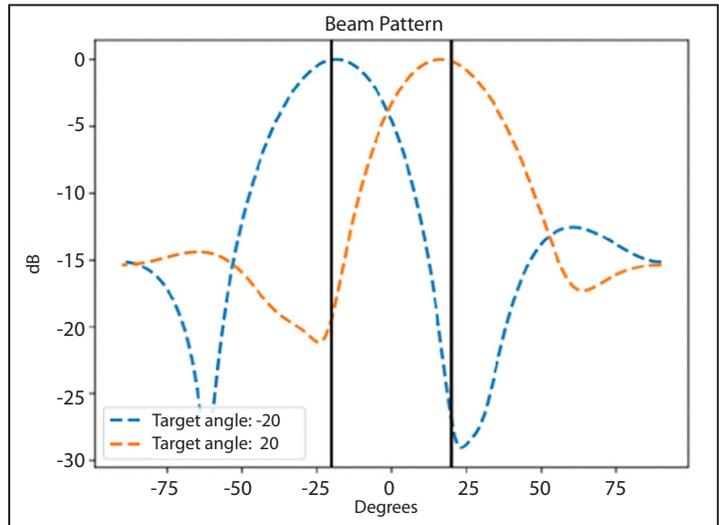


Figure 9. Beam patterns for targets #1 and #2.

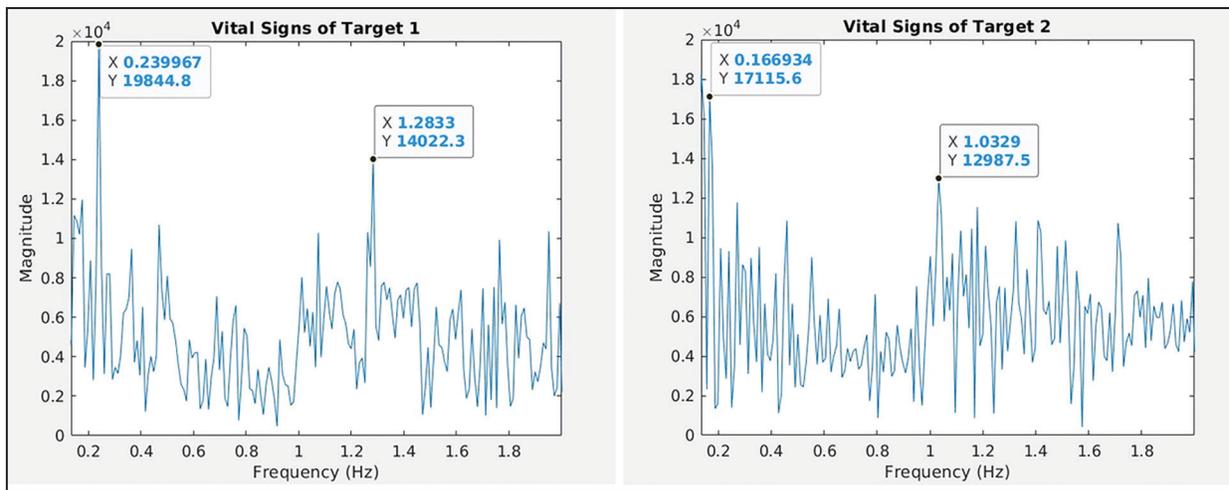


Figure 10. Frequency spectrum of target #1 (left) and #2 (right).

Table 1. Differences in cost between the prototype and a PCB implementation.

Prototype	PCB Implementation
Phase Shifters: \$32 per (x8)	Phase Shifters: \$19 per (x8)
Antennas: \$30 per (x8)	Antennas: \$15 per (x8)
Multiplexers: \$5 per (x8)	Multiplexers: unnecessary
Amplifiers: \$0.56 per (x8)	Amplifiers: \$1 per (x8)
RF Transceiver: \$5,500	RF Transceiver: \$150
Arduino Mega 2560: \$42	FPGA: \$10 per
Breadboarding costs: \$5	PCB fabrication costs: \$10 to \$100
Digital Signal Processor: \$800	DSP Conducted on Controller: \$0
Power divider: \$1000	IC Power Divider: \$20
Power Supply: \$500	Power Supply: \$20
Rough Total: >\$8000	Rough Total: >\$500

2.6. Costs

To visualize the costs of the prototype, each subsystem in Figure 2 was listed out in the left column of Table 1. Understandably, the prototype costs are high because of expensive SDR hardware, namely the \$5,500 USRP2920. The right column in table 1 illustrates the team's approach to reduce the VSM's cost. The clearest method of cost reduction would be to choose a cheaper receiver, preferably one that is small enough to fit onto a printed circuit board (PCB). Changing the controller into an FPGA (field programmable gate array) would also help, both in terms of cost and computational power. For mass production, cheaper amplifier and power regulation ICs can be used in the design of a single PCB. In this, the overall system cost drops to around \$500, which is more than an order of magnitude cheaper than the current prototype.

3. Educational Outcomes

The capstone design team for this project consisted of four electrical engineering students and one computer engineering student, all of whom were graduating seniors. The makeup of the team was determined by the students' mutual interest in working with each other. Upon grouping together, the students picked their advisor, Dr. Athina Petropulu, because of their unanimous desire to gain experience in signal processing and wireless communication systems. Once the advisor-capstone team connection was formed, students were tasked with developing a project topic. The advisor initially proposed her lab's DPS technology and its potential applications in VSM to the team; however it was up to students to decide how to apply DPS in their own unique project idea. After about a week of deliberation, the team decided to follow through with a multitargeted infant monitoring system, given the

need for improved infant VSM in nursery settings. Since the capstone design course at Rutgers University requires students to complete the project within 2 semesters, team members unanimously agreed that the project scope was feasible enough to design and test within the required timeframe.

Upon completing the 2-semester long project, team members were surveyed by the team leader (Daniel Gore) to assess the educational outcomes of the project via an in-person meeting. No specific

list of questions was followed; rather, the team members engaged in a conversation that the team leader was able to generate meeting notes from (like many project tag ups in industrial settings). Once the meeting notes were fully compiled, the team leader was able to make numerous determinations. For starters, students agreed that working on this project broadened their knowledge on electronic circuitry, specifically RF circuits, and signal processing. In terms of hardware, three team members gained hands-on experience with amplifiers, phased arrays, SDR, and test engineering. The other two team members who centered more towards software gained experience in concepts such as C++ for Arduino control, algorithm design in MATLAB and Python, and FFTs. Overall, the team learned new skills in five total software programs to make the VSM work: C++ (via the Arduino IDE), Python, MATLAB, LabView, and Excel. Team members also learned how to apply information from their undergraduate classes, ranging from introductory circuit design to more advanced topics including digital signal processing and analog electronics. However, much of the needed theory for this project is not typically taught in undergraduate courses, so for concepts in radar engineering, team members relied on literature review.

In the end, all five students admitted to developing skills and interests in RF engineering and radar, signal processing, or testing at the systems level. These developments paid off for the team, as the project won first place (out of 52 teams) at their department's capstone exposition and a distinguished "Best in Research" prize. Regarding the effects of its success on a department-wide level, this project set an example for future capstone projects whose teams want to compete for first place. By applying innovative technologies like DPS that have little to no known documentation, or by integrating multiple advanced

concepts into one system, judges at capstone design expositions may express increased interest in their evaluations of a project.

4. Conclusions and Future Work

This paper has discussed the integration of DPS technology into a VSM. During the project life cycle, the team developed a multitargeted VSM with a custom analog controller and beam steering backend to wirelessly collect a target's heart rate and breathing rate. Experimental results illustrate the device's efficacy on human subjects, which motivates future efforts to scale down the device size for improved performance and lower cost. In terms of the system's future development, the team began organizing the design of an all-in-one PCB. The new device will integrate a FPGA, DC amplifier circuitry, and RF front end on a single board. The FPGA will act as a programmable PWM controller that feeds a similar analog frontend to steer the beam on the phased array, and a digital signal processor will compute the vital signs of each measured target with an FFT. Using duplexing techniques, the onboard RF transceiver will act as a pulse recovery system in receive mode to recover each target's vitals, and a telemetry hub in transmit mode to send the recovered vital sign information to a computer for display purposes. Finally, power amplifiers will be added at the output ports of the DPS hardware to ensure that the FFTs produced by the board are less noisy than the results in Figure 10.

As development continues with the VSM, not only is the team convinced of its practical potential in pediatrics, but also its positive effects on their educational journey in becoming well-rounded electrical engineers. All five team members developed a foundational understanding of RF and radar concepts with little theoretical background, and instead relied on hands-on learning and literature review which was conducted only when it was necessary. Less niche skills, including those in Python, MATLAB, and signal processing, were also developed; however most students had an introduction to such concepts from prior courses. For future senior design teams who wish to continue the VSM development, team members will be able to learn the same skills at a much faster pace now that documentation of the VSM prototype already exists. This will allow students on future teams to gain additional knowledge within a two-semester-long timeframe while working on the same effort, namely in RF PCB design and implementing digital signal processing algorithms on FPGAs.

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