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IEEE Member #:80225649

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Dear members of the student design contest committee,

With this letter, I would like to express my support for the proposal entitled "*Efficient Modular FMCW Beamtracking SIMO System for Vision Aid*" prepared by the **ORASIS team**. The proposal is being submitted to the 2025 IEEE AP-S Student Design Contest: Propose a beam-tracking antenna system capable of real-time tracking a moving target and provide educational materials to explain it.

Five undergraduate (in a 5 year curriculum) students of ECE Department of Electrical and Computer Engineering, University of Patras, Greece, comprise **ORASIS** team (in alphabetical order, First Name, Last Name):

1. Mr. Alexandros CHRISTOPOULOS is a 5th year undergrad student.
2. Mr. Konstantinos-Fotios KYRIAKOPOULOS is a 3rd year undergrad student.
3. Ms. Violeta MEGARI is a 3rd year undergrad student.
4. Mr Vasileios MPANAKOS is a 3rd year undergrad student.
5. Mr Charalampos PAPADOPOULOS is a 3rd year undergrad student.

Furthermore, I would like to state that I intend to be and I will be with great pleasure the advisor of ORASIS team. I will also provide them access to Electromagnetic software we have in the lab (Ansys HFSS), microwave circuits analysis software (Keysight ADS) access to the laboratory equipment and workshop for board and antenna fabrication.

Please find attached the proposal

Stavros Koulouridis, Professor
Dipl.-Ing, Ph.D
Director of RF, Microwave and Wireless Communications Laboratory

Efficient Modular FMCW Beamtracking SIMO System for Vision Aid

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I. INTRODUCTION

Vision loss is a disability from which many people suffer all around the globe. People with visual blindness face many difficulties during their daily routine. Many of them are related to basic outdoor activities like going for a walk or crossing the road. Unfortunately, numerous accidents have been recorded, caused by the blind person's surroundings, including other pedestrians and moving bicycles. There are several vision-aid systems. For example, [1] is an acoustic navigation system supported by several sensors to detect targets and create a virtual map. Then it converts it to a 3D audio scene and generates a binaural audio sound pointing to the direction of each target. Alternatively, a compact radar system with a tracking Inertial Measurement Unit (IMU) and a SAR imager for nearby objects detection is proposed in [2].

In this paper, we suggest a low-cost, compact and easy to implement beam-tracking Single Input Multiple Output (SIMO) Radar based on Software Defined Radio (SDR) implementation which is capable of tracking moving targets in real time using off-the-self components and beamforming.

II. PROPOSED SYSTEM

The system will operate at 5.8 GHz Industrial, Scientific, and Medical (ISM) frequency band and is shown in Fig. 1. It can be divided into two sections: the front end and the back end. The latter is comprised of one Raspberry Pi (RasPi) and a bladeRF 2.0 micro xA4 SDR module. The RasPi is chosen due to its performance and compact size and will carry out the main computations.

One transmission port from bladeRF passes the signal through a Power Amplifier (PA) to a 1-to-4 power splitter. Each output from the splitter is fed into a phase shifter, in which a specific phase angle is applied to steer the transmission antennas' beam in the desired direction thus achieving analog beamforming. In the receiving part of the front end, two antennas receive the signal, which, after passing through a Low Noise Amplifier (LNA), is fed into the two receiver (Rx) channels of the SDR.

Thanks to the antenna setup and analog beamformer on the transmitter (Tx) channel, the system is capable of operating in two modes: scanning and beam tracking. The scanning mode is initialized during the system's startup, and, in this state, the beam will be steered horizontally, searching the area in front of the system's user for moving obstacles. When scanning is completed, detected targets will be evaluated by signal processing and, after selecting the one closer to the user, the radar will enter the second mode and start tracking this target.

The Multi Signal Classification (MUSIC) algorithm will be used to process the received data and estimate the Direction of Arrival (DoA) of the reflected signal. To estimate each target's position and velocity, a Frequency-Modulated Continuous Wave (FMCW) is employed. This approach was selected as the benefits of FMCW (position and velocity accuracy, processing time) make it more suitable compared to other techniques (Stepped Frequency Continuous Wave, pulsed, etc.). The post-processing data is visualized on an external laptop screen. The whole system is placed on a wearable vest.

Previous research, [3], has shown that MUSIC can estimate the DoA of a relatively slow-moving target in real time, hence enabling the antennas' beam to be dynamically adjusted through the Tx beamformer to follow the movement of the tracked object. Low processing time will provide for the system the capability of integrating the two operating modes, enabling periodic scans of the area ahead while tracking a specific target. If a new closer target is acquired during these sweeps, the system will switch to tracking the newly acquired target.

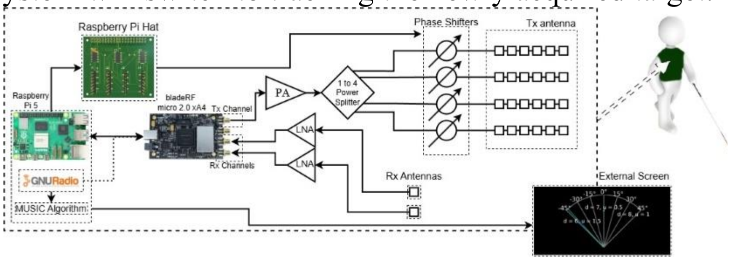

Figure 1 Block diagram of the proposed system

III. MAIN RADAR COMPONENTS

A. Software Defined Radio Board

BladeRF 2.0 module [4] is a USB3, 2x2 Multiple Input Multiple Output (MIMO) software-aided radio transceiver capable of implementing numerous transmission schemes through suitabe programming. Apart from the compact size and low-cost, it provides an adequate frequency range which allows us to select a center frequency of 5.8GHz with 56MHz bandwidth. Also, the ability to achieve a sample rate equal to 122.88 MS/s, with a 12 bit ADC/DAC resolution, enhances real-time processing capabilities. To reduce the total cost and achieve lower processing time, we configure the 2x2 MIMO streaming to 1x2 SIMO by disabling the one transmitter. The control of the SDR can be easily implemented with GNU Radio, a free software development toolkit that can be used for creating signal processing and SDR systems and simulations. Furthermore a 49KLE Cyclone V FPGA performs the baseband processing.

B. Antennas

Patch antennas [5] are made up of a metallic sheet placed above a metallic plane used as ground plane. These two metals are separated by a dielectric material (substrate). This kind of antenna is widely used in radar applications due to its compact nature, versatility, small size, light weight and low fabrication cost. They are considered directional antennas (meaning they radiate mostly towards one direction). When combined to synthesize an antenna array, their directivity is significantly increased, making them ideal for beamforming applications.

The proposed system's front end consists of four series-fed patch antenna arrays in the Tx port and a single patch in each of the two Rx ports. The antennas will be fabricated according to [6]. In [6], patches with novel geometry are designed for applications at 5.8 GHz ISM frequency band. Each patch will be designed as the superposition of two tapered patches with lengths L_1 and L_2 and a curved upper edge. The degree of superposition $s=L_2/L_1$ and curvature of the upper edge will be selected such that the desired side lob level and low reflection coefficient is achieved around the operating frequency. A Rogers RO4003C [7] dielectric material with dielectric constant $\varepsilon_r = 3.55$ and thickness h = 1.524 mm will be used as the dielectric substrate. Six of these patches will be placed together to form a series fed patch antenna array with a coaxial feed at the center of the array. This geometry achieves a gain of almost 14 dBi, a 3-dB beamwidth of 20° and –20 dB side lobe level in E-plane around the radar's operating frequency. Low side lobe level means that the antenna's radiation pattern (a measure of the radiated power distribution in the space around the antenna) consists of a major beam towards a specific direction and significantly smaller beams in other directions, which allows less undesired signal interference and enhancement of signals aligning with the direction of the major lobe.

Four series fed patch arrays placed at λ/2 distance will form our Tx antenna array enabling beam control in the horizontal plane. The gain of the combined series fed patch array is expected to reach 17dBi.

C. *Phase Shifters & Splitter*

Beamforming at Tx channel is achieved by a digitally controlled phase shifter that utilizes a 6-bit binary word, with each one representing a specific angle. The 360° range is divided into $2^6 = 64$ discrete angles, resulting in an increment step of 5.625° from 5.625° to 354.375°. This phase shifter is based on HMC649A chip [8].

The power splitter [9] divides the main signal into four sub-signals, directing them to the phase shifters. At the same time the binary words generated by the output pins of the RasPi microcontroller adjust the phase of each transmission antenna's identical signal, shifting the beam towards the desired direction.

D. *Raspberry Pi*

The RasPi [10] is a microcomputer used for the signal processing and transferring of the data to the main computer for visualization via Wi-Fi but also for the control of the phase shifters. To make it more modular and easier to connect, the phase shifters will be controlled by a custom designed Printed Circuit Board (PCB), and an in-house designed and fabricated RasPi hat, which will be connected to the GPIO of the RasPi.

Through serial communication it controls three 8-bit shift registers, the outputs of which then control the angle of each phase shifter.

IV. *Radar Elements*

A. *Maximum Range and Link Budget*

The radar's maximum detection range is given by the Radar Equation [11]

$$R=\sqrt[4]{\frac{Pcw\cdot G_t\cdot G_r\cdot \lambda^2\cdot \sigma_T\cdot L_2}{(4\pi)^3\cdot \delta_R}}$$

where Pcw is the input power at the transmitting antenna, G_t the transmitter's antenna gain, G_r the receiver antenna gain, λ the wavelength, σ_T the radar's cross section, L_2 the two-way atmospheric transmission factor and δ_R the receiver's sensitivity.

Radar detection range can be improved, by both enhancing the Pcw at Tx side and receiver's sensitivity. To that end a PA [12] with a Gain of +13dB will be added, right after the SDR's transmitter output. In addition, in each of the two receiver's path we add a LNA [13], with Gain equal to +23dB.

After taking into account the 1-to-4 power splitter and the phase shifters insertion loss and cable losses, the radiated power from the array will reach +18.6dBm considering typical +5.1dBm CW output power of the BladeRF. In our system, we have: $Pcw=1.6dBm$, $G_t=17\ dBi$, $G_r=5dBi$, $\lambda=5.17\ cm$, $\sigma_T(human)=1\ m^2$, $L_2= 0.99$, $\delta_R=-81.5\ dBm$. Radar Equation gives an approximate value of R=14.4m. If the target is a bicycle (front-faced profile) then $\sigma_T=0.1\ m^2$ and the max detection range equals to R=8.1m. It is important to mention that all the values above have been calculated, including all the system's losses and the worst-case scenario.

B. *Frequency Modulated Continuous Wave*

In our radar, we are going to implement Frequency-Modulated Continuous-Wave (FMCW). This is a type of radar transmission technique which radiates continuous transmission power. What differentiates FMCW from other continuous wave (CW) radars is that an FMCW system emits a single pulse at every frequency of the employed frequency range. The frequency change is dictated usually by the SDR command module. The advantage of FMCW over traditional pulse radar systems, which measure the runtime from the moment the signal is emitted until it is received back, is that the runtime is measured using the beat frequency (f_b), which is the absolute difference in frequency between the transmitted and the received signal

$$f_b=|f_{T_x}-f_{R_x}|$$

The received signal consists of the In-phase (I) and the quadrature (Q) components. The I signal is a cosine with frequency f_b, while Q is just shifted by 90 degrees, making it a sine wave. The target's range can be calculated from

$$R=\frac{c\cdot Tc\cdot f_b}{2\cdot BW}$$

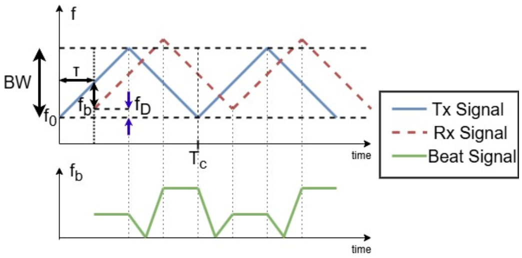

Figure 2 FMCW Signals

where c is the speed of light, T_c the chirp period and BW the bandwidth of our system. The relative speed of the target can be derived from the Doppler shift of the signal

$$v_r=\frac{f_D\cdot c}{2\cdot f_0}$$

where v_r is the target's relative velocity, f_D the doppler shift frequency and f_0 the start frequency of the chirp signal. To distinguish the beat frequency and Doppler shift frequency we use a triangular chirp as shown in Fig. 2. Using the fundamental design equation of the FMCW system, the parameter values depicted at Table I are considered.

Table I FMCW parameters

Center Frequency	5.8GHz
Operation frequency range	5.772-5.828GHz
Bandwidth (BW)	56MHz
Chirp Waveform	Triangular
Chirp period (T_c)	1ms
Radars Detection Range	11.2m
Range Resolution (ΔR)	2.7m
Max Unambiguous Velocity (v_{max})	13m/s

C. Doppler Map

The received data is a sum of multiple frequency shifted signals due to the many objects that reflect the transmitted signal. To find the range of the actual target we take the FFT of our beat signal, creating a frequency space where the amplitude peaks indicate targets. Then by calculating the range for each responding frequency, the range spectrum is determined. Taking N number of chirp samples, the velocity of the target can be calculated from the phase difference of each chirp, since the delay is correlated with the dislocation of the object. So, by taking N number of chirps and stacking them up in the Y axis, a 2-D FFT can be implemented and create the Range-Doppler map which indicates the velocity and the range of each target [14].

D. Direction of Arrival Estimation

Estimation of the Direction of Arrival (DoA) of the incident signal is a crucial part of our system since it provides information about a target's position, and it comprises a necessary parameter for performing beamforming. The MUSIC algorithm will be implemented to estimate the DoA [15]. MUSIC is a decomposition algorithm which divides the received data into the incident signal and the noise subspaces and estimates DoA based on the orthogonality of these two.

Assuming a receiver consisting of a uniform linear array of M elements, the vector consisting of the weights of each element (known as the steering vector) can be written as:

$$a(\theta)=[1 \quad e^{j\pi sin\theta} \ldots \quad e^{j\pi(M-1)sin\theta}]$$

where θ is the DoA and for which $-90°\leq\theta\leq 90°$ is true. The received data can be expressed in a matrix as a sum of the incident signal and noise vectors. Their covariance matrix is formulated based on the signal's independence from noise. Using eigenvalue decomposition it can be written as the sum of the signal and noise subspaces. Assuming ideal conditions, these subspaces are orthogonal to each other and thus the steering vector and θ can be found from

$$a^H(\theta)U_N=0$$

where U_N represents the noise's eigenvector matrix.

In real world applications, orthogonality is not always true, thus the covariance matrix is replaced by its estimator and DoA calculation is reduced to minimum optimization search and hence

$$\theta_{MUSIC}=arg\left[min\left(a^H(\theta)U'_N U'^H_N a(\theta)\right)\right]$$

where U'_N is U_N's estimator. The spectrum function can be expressed as:

$$P_{MUSIC}(\theta)=\frac{1}{a^H(\theta)U'_N U'^H_N a(\theta)}$$

the peaks of which represent the estimated DoAs or $\theta_{estimated}=\theta_{MUSIC}$ when P_{MUSIC} is maximum.

MUSIC is considered a super-resolution algorithm owing to its high resolution and precision in DoA estimation. Its restrictions are that it requires prior knowledge of the number of the existing targets, and it can distinguish M-1 targets where M is the number of elements in the receiver array. In this implementation, the receiver array consists of two antennas and thus only one target will be used per beam.

E. Beamforming

For the Tx setup, four antenna elements are arranged in a row, spaced λ/2 apart from one another, to create a specific wavefront that reaches a target. Depending on the direction of the signal, each antenna element is at a different distance from the desired wavefront axis, causing a delay in its arrival. If this delay is not taken into consideration, the signals can interfere destructively and cancel each other out, preventing the formation of a coherent beam. However, if the appropriate delay is applied to each element relative to the others, the primary beam can be formed at the desired transmission angle. Assume an angle θ, where θ = 0 (the boresight direction) is defined as perpendicular to the antenna array, while positive and negative values of θ represent angles to the right and left respectively. For the signal to form the desired wavefront, each element must delay its transmission by:

$$\Delta t=\frac{d}{c}sin\theta$$

so that all signals converge in phase at the wavefront when the last element's wave reaches it.

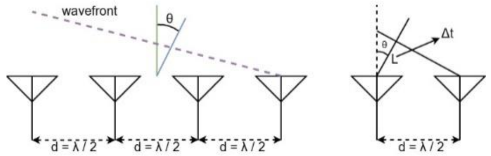

Figure 3 Beamforming Setup

Since time shift and phase shift are related through the equation:

$$\Delta\Phi=2\pi f\Delta t=2\pi\frac{d}{\lambda}sin\theta,$$

and the spacing between the elements is $d=\frac{\lambda}{2}$, the phase delay calculation simplifies to:

$$\Delta\varphi=\pi sin\theta$$

which corresponds to the phase shift required between adjacent elements to form the beam. If θ is positive, the phase shifts can be represented in an array

$$a(\theta)=[1\ e^{j\Delta\varphi}\ e^{j2\Delta\varphi}\ e^{j3\Delta\varphi}]$$

If θ is negative, the array is written as

$$a(\theta)=[e^{j3\Delta\varphi}\ e^{j2\Delta\varphi}\ e^{j\Delta\varphi}\ 1].$$

V. IN-CLASS DEMONSTRATION AND VISUALIZATION

The proposed system can be easily assembled since it is modular and portable, making an in-classroom demonstration possible. A student can assemble the system according to the following instructions: Firstly, power up the RaspPi, the SDR and the phase shifters using a portable power supply. Then, connect the SDR to the RasPi via USB and to the analog beamformer along with the PA. Connect the RasPi's GPIO pins to its hat and attach its outputs to the phase shifters. Next, connect each antenna to the output of the equivalent phase shifter. For the receiver part, attach each antenna to the Rx channels after connecting them to the LNAs. RasPi and SDR will be pre-programmed to function properly for the demonstration.

After assembling the system, a person can wear the vest, and another person can walk towards or away from the first one to demonstrate the beam tracking capability of the radar. Multiple people can also stand in different angles within the radar's field of view or walk to confirm the system's ability to detect multiple objects and choose which one it will eventually track. This demonstration will allow students to explore the basic concepts of beam-steering antennas that enable beamforming and beamtracking.

The resulting data can be visually depicted in a virtual environment, as shown in Fig. 4. Assume a target in distance R, angle θ, and velocity v. After the received signal is processed the calculated beat frequency will be $f_b=1500\ Hz$, so from target's range formula $R=4m$. The calculated doppler shift frequency is $f_D=58Hz$, so from target's velocity formula $v=1.5m/s$. After using the MUSIC for DoA, angle is found $\theta=-42.7^{\circ}$. For the above calculations we assume $c=3x10^8 m/s$, $BW=56MHz$, $T_c=1ms$, $\lambda=51.7mm$, $SNR_{receiver}=10$, $N=1000$.

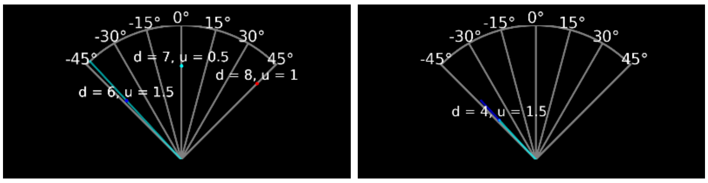

Figure 4 Visualization of the two operation modes, scanning & tracking

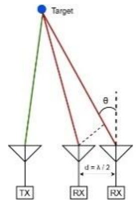

Figure 5 System Transceiver during operation

VI. BILL OF MATERIALS

Raspberry Pi	\$80
BladeRF xA4	\$540
Power Amplifier	\$170
Splitter	\$127
RF Phase Shifters (x4)	\$408
Raspberry Pi accessory hat	\$5
Coaxial Cables	~\$40
LNA (x2, \$48.15 each)	\$97
Total	**\$1467**

Antennas will be fabricated in the lab thus they don't contribute to the total cost.

VII. REFERENCES

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