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Software Configurable Multi-mode Radar Sensor System for Range Tracking and Life Sensing

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***Abstract*— In this paper, a software-configurable multi-mode radar is demonstrated with four detection modes that can be adaptively chosen with a microcontroller-based signal synthesizer. These include Doppler, frequency shift keying (FSK), frequency modulated continuous wave (FMCW), and stepped frequency continuous wave (SFCW). For the FMCW and SFCW mode, a nonlinearity compensation technique is implemented in the software, whose advantages are experimentally demonstrated. Range tracking in the FSK mode and life monitoring in the Doppler mode are also realized. The software-configurable multi-mode sensor has a potential impact on IoT applications by adaptively trade among spectrum usage, computational load, sensitivity, resolution, and accuracy.**

***Keywords*— Doppler, FMCW, FSK, nonlinear compensation.**

I. INTRODUCTION

Radars have numerous applications in modern life, with anything involving range or velocity detection. There are different output waveforms that are used, with their uses and advantages for different applications. Doppler radar is mainly used for velocity detection and can be used to track the speed of targets, or even the respiration rate and heartbeat of a human target. FSK, FMCW, and SFCW can all be used for range detection, with their own strengths, benefits, and optimal detection scenario. These three modes also have their own methods of extracting velocity with a Doppler frequency as well. Since these mentioned modes all have their ideal applications, it can be advantageous to have a radar that can be configured in real-time among multiple modes to adaptively adjust to the detection environment. There have been other works on the subject of a single radar system incorporating multiple modes or functions [1]-[5]. However, there have not been any works to incorporate the four mentioned radar modes using software configuration. With a software configurable multi-mode radar, a single system could accomplish multiple tasks simultaneously in the IoT space. The system can be further improved since the modes would be fully customizable through software.

Such a system can be advantageous for continuous monitoring of people in a living environment, as the location of a user in a room or environment can be used for various IoT applications. Also, the Doppler mode of the radar can be used for health monitoring of stationary users. The ideal use case would use one or more radar systems for more accurate location and health monitoring. The FMCW, SFCW, and FSK modes would be for location tracking. Having advantages of requiring less bandwidth and computational load, FSK would be ideal for simple environment with a small number of active occupants, since range detection for this case is limited by its unambiguous range and FSK relies on motion to extract target information. FMCW could be used for more complex environments, since it has a larger unambiguous range related to its chirp length. It detects range of all targets, irrespective of whether they are moving, while also offers range-Doppler analysis to extract moving targets. The Doppler mode of the system can be used for health monitoring of stationary users as well. The advantage of including an SFCW mode is that it has the potential to combine the range detection of FMCW mode and the direct Doppler/interferometry-based health monitoring at each discrete transmit frequency point [6]. Since the SFCW waveform is divided into multiple steps of constant frequency, these frequencies can be grouped together and plotted over time to output multiple Doppler responses, that can be processed to monitor the health of any users in the environment.

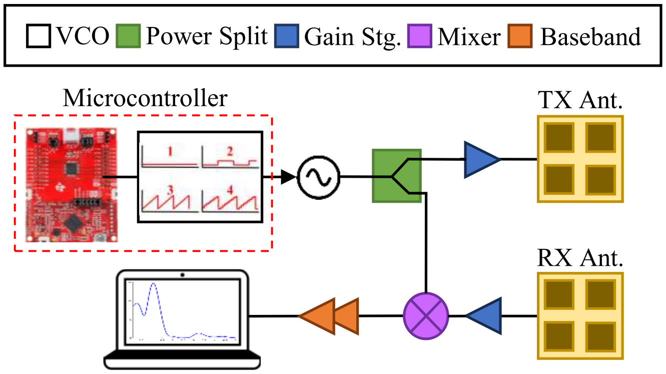

Fig. 1. System Radar block diagram, with the MSP-EXP430FR2355 inputting customizable waveform modes into the VCO input. The return signal is then received and processed by a computer.

Section II provides an overview of the system design and implemented custom nonlinearity compensation waveforms. Section III of this work details the experimental results of the system from all four modes. Last, section IV provides a conclusion of the work presented.

II. SYSTEM DESIGN AND NONLINEARITY COMPENSATION

To accomplish a software configurable radar, the MSP-EXP430FR2355 microcontroller was selected for a direct-conversion RF front-end as shown in Fig. 1. This was coded with software in C++ to output an analog voltage signal up to an internal 2 V reference. The period of the output signal is

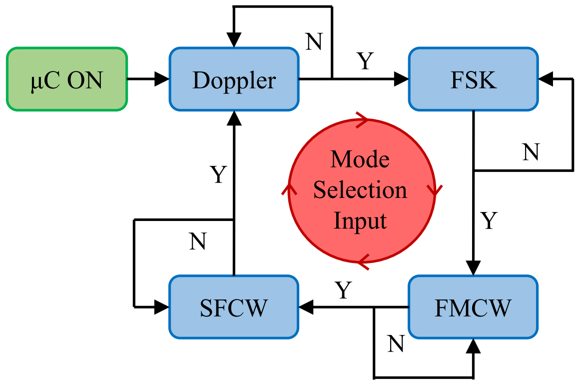

Fig. 2. Code flow chart, showing the order that the modes are stepped through in the code when the user makes a mode selection input.

configurable and set as a variable in the code. When the system is powered on, the default mode is the Doppler mode. In this work, a button on the microcontroller acts as an interrupt to change to the four pre-defined modes, described in Fig. 2., however this interrupt can be implemented in software for future systems. The waveforms, after microcontroller configuration, are set by loops in the code. A simple count steps through the user defined modes, which also allows for the waveforms to be fully customizable with the inclusion of a header file that the user can create. The four modes in this work are described below.

A. System Design

The Doppler mode is the default mode when powered on. For this case, a single value of 0 is repeated in the code. This corresponds to a constant output voltage of 0 V, resulting in a constant Doppler frequency output from the VCO of 5.8 GHz.

The second mode in the system is the FSK mode. For this mode, a loop is implemented in the code that switches from 0 V and 0.2 V at the desired switching period of 4 ms, set by the user. This results in output frequency of 5.84 GHz and 5.87 GHz, a frequency difference of 30 MHz. using the FSK maximum unambiguous range equation, the theoretical maximum unambiguous range in this mode is approximately 15 m.

For the third output mode, an FMCW mode is utilized. This is also implemented with a loop in the code. For this mode, the count increases the output value linearly, from 0 V to 2 V over the user defined period of 4 ms. This results in an output sawtooth ramp signal from the VCO from 5.8 GHz to 6.2 GHz. This corresponds to a bandwidth of 400 MHz. This bandwidth and a period of 4 ms can be used in the FMCW range resolution equation to have a theoretical range resolution limit of 0.375 m.

The final mode, SFCW, is implemented with another loop in the code that steps through a custom sequence of values, in a user created header file. For this system, the values are split into 40 steps from a similar 0 V to 2 V with a step size of 0.05 V. The steps are also divided on the time axis by increasing the value every 100 µs. This results in a stepped output function from the VCO of 5.8 GHz to 6.2 GHz with an overall bandwidth of 400 MHz. The 40 steps give the waveform a smaller, more instantaneous bandwidth of 10 MHz.

B. Nonlinearity Compensation

It is known that there are nonlinearities that exist when it comes to the VCO tuning curve. Unlike the ideal case, a linear ramp input voltage will be distorted at the output resulting in a nonlinear chirp out of the VCO. A software configurable system can easily compensate for this issue since it can be updated to include a custom output waveform that accounts for this nonlinearity. The following experiment shows the results of custom compensation waveforms for both the FMCW and SFCW modes.

First, to determine the correction needed, the VCO's tuning voltage was characterized. For this work, an Analog Devices HMC358 was used. Then, a curve fitting technique was applied to the graph to characterize the tuning voltage plot. A technique to determine the appropriate nonlinear chirp was used as described in [7]. This curve was also divided into steps to make a compensated SFCW chirp. The compensated and uncompensated SFCW chirps are shown in Fig. 3.

III. EXPERIMENTAL RESULTS

The radar front-end used in this work [2] operates from 5.6 GHz to 6.2 GHz. This system was selected due to its accessible tune input for the testing of the previously mentioned custom waveforms.

A. FMCW & SFCW Compensation

To test the effectiveness of the compensating waveforms, an experiment was conducted varying the distance of a corner reflector between 1 m and 2 m, at 10 cm increments. Data was recorded for both the FMCW and SFCW modes using an NI DAQ and recorded on LabVIEW. The resulting data was processed by taking an average of the FFT'ed baseband frequency responses. It was then converted from frequency to range.

The resulting peaks were plotted for each distance, compared with the ideal range slope. Both uncompensated and compensated chirp range results are plotted in Fig. 4. For the FMCW case, both the average and maximum error were reduced by 0.085 and 0.14 respectively. Also, the SFCW case had both the average and maximum errors reduced, by 0.01 and 0.07respectively. The calculated errors for both modes are shown in Table I.

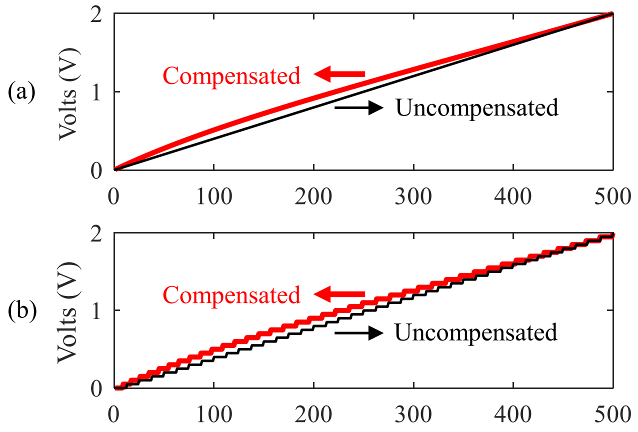

Fig. 3. FMCW (a) and SFCW (b) custom compensated control voltage plotted against the uncompensated waveform.

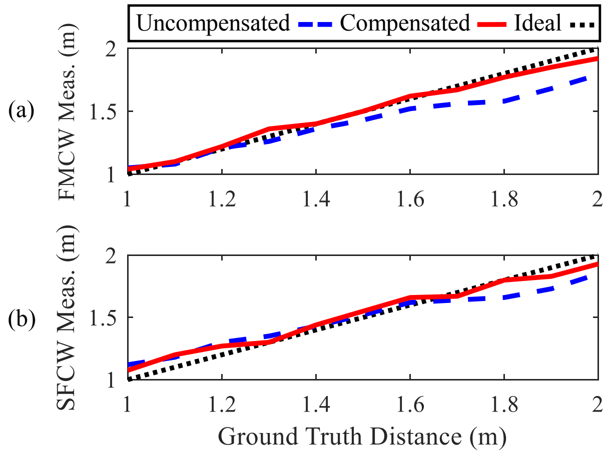

Fig. 4. FMCW (a) and SFCW (b) custom compensation range results compared with the uncompensated case.

TABLE I. COMPENSATION EXPERIMENT ERROR

Error (m)	**FMCW**		**SFCW**	
	Unomp.	***Comp.***	***Uncomp.***	***Comp.***
Average Error	0.09	0.01	0.02	0.01
Max Error	0.22	0.08	0.17	0.10

B. *Doppler & FSK*

Doppler motion-sensing mode of the system was characterized by detecting a 0.1 mm actuator motion at 1 Hz, placed approximately 0.5 m from the radar. A 20 s reading was taken, and the actuator motion was then extracted after taking an FFT of the time domain data. This resulted in a Doppler response output of a similar frequency being sensed by the radar seen in Fig. 5.

To determine the range detecting capability of the FSK mode, an experiment was conducted where the radar system was placed in an empty hall, and a human subject walked back and forth in front of the radar. This was done with a turning point approximately 3 m, then 5 m in front of the radar. Then, the returned beat frequency data was recorded over time and compared in signal processing using arctangent demodulation [8]. The resulting phase difference was converted to range over time in Fig. 5.

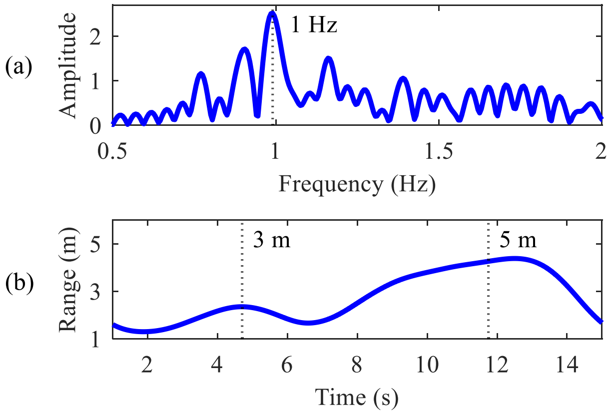

Fig. 5. Doppler experiment frequency plot (a) of a 0.1 mm actuator motion at 1 Hz. FSK experiment range plot (b) over time with 3 m and 5 m turning points.

IV. CONCLUSION

A software-configurable multi-mode radar was demonstrated, with four modes including Doppler, FSK, FMCW, and SFCW. A nonlinear compensation technique was used that leverages the use of software defined modes. An experiment was carried out to show that this compensation resulted in an increase in both the average and absolute error for both the FMCW and SFCW modes. Range detection was also proven for the FSK mode, with health monitoring of stationary targets also demonstrated using the Doppler mode of the radar. All the experiments show that these software configurated modes can be used together in a living environment to track users for their range and stationary health monitoring. This is advantageous as this information can be used in conjunction with the IoT for various applications in an environment.

ACKNOWLEDGEMENTS

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REFERENCES

[1] [N. Naseh, M. G. Bardeh, and K. Entesari, “A 5.8-GHz Phased Array FMCW Doppler Radar Front End for Object Localization and Movement Tracking in 65-nm CMOS*,” IEEE Transactions on Microwave Theory and Techniques*, pp. 1–15, 2023, doi: 10.1109/TMTT.2023.3259527.

[2] J. Wang and C. Li, “A Portable Doppler/FSK/FMCW Multi-mode Radar With Analog DC Offset Cancellation for Biomedical Applications,” *2019 United States National Committee of URSI National Radio Science Meeting (USNC-URSI NRSM)*, Jan. 2019, pp. 1–2. doi: 10.23919/USNC-URSI-NRSM.2019.8712903.

[3] W. Kang, S. Qian, Z. Sang, and W. Wu, “Investigation of Stepped-Frequency Hybrid Modulation Radar for Respiration Monitoring, 2-D Localization, and Moving Target Tracking,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 70, no. 7, pp. 3700–3712, Jul. 2022, doi: 10.1109/TMTT.2022.3175215.

[4] G.-H. Ko, J. Y. Park, K.-I. Oh, Z. Jin, S.-H. Kim, and D. Baek, “Multi-Mode Signal Generator for K-band Radar Sensor Applications,” *2021 International Conference on Electronics, Information, and Communication (ICEIC)*, Jan. 2021, pp. 1–4. doi: 10.1109/ICEIC51217.2021.9369803.

[5] Y. Yuan, C. Lu, A. Y.-K. Chen, C.-H. Tseng, and C.-T. M. Wu, “Multi-Target Concurrent Vital Sign and Location Detection Using Metamaterial-Integrated Self-Injection-Locked Quadrature Radar Sensor,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 67, no. 12, pp. 5429–5437, Dec. 2019, doi: 10.1109/TMTT.2019.2931834.

[6] M. Mercuri, D. Schreurs, and P. Leroux, “SFCW microwave radar for in-door fall detection,” *2012 IEEE Topical Conference on Biomedical Wireless Technologies, Networks, and Sensing Systems (BioWireleSS)*, Jan. 2012, pp. 53–56. doi: 10.1109/BioWireless.2012.6172729.

[7] M. Vasconcelos, P. Nallabolu, and C. Li, “Range Resolution Improvement in FMCW Radar Through VCO’s Nonlinearity Compensation,” *2023 IEEE Topical Conference on Wireless Sensors and Sensor Networks*, Jan. 2023, pp. 53–56. doi: 10.1109/WiSNeT56959.2023.10046230.

[8] A. Wang, “FSK radar and transponder systems for range tracking and vital signs sensing of multiple targets,” Thesis, 2021. Accessed: Jul. 21, 2023. [Online]. Available: https://ttu-ir.tdl.org/handle/2346/87592Univ., Lubbock, Texas 2021