

Multi-Modal Standoff Through-the-Wall Imaging Radar and Personnel Location System Using Biometric and Gait Responses

David Boutte, James Hogg, Steven Hunt and Allan Hunt

AKELA Inc.

5551 Ekwill St. Suite A

Santa Barbara, CA 93111

UNITED STATES OF AMERICA

dboutte@akelainc.com

ABSTRACT

The ability to detect and locate stationary and moving individuals through building walls from significant standoff distances provides increased situational awareness and considerable tactical advantage to security and military personnel. This paper discusses the design, implementation and detection algorithms of an ultra-wideband (UWB) compact standoff imaging radar for through the wall detection and identification of human targets. The conceptual system operates in S-band and operates using a UWB stepped frequency mode for high-resolution imaging and location and a continuous wave (CW) mode for high resolution Doppler estimation. Results from biometric and gait exploitation algorithms presented in this paper are focused on exploiting the micro-Doppler signatures present in the UWB response. Micro-Doppler has previously been used for both personnel detection using respiratory and cardiac response in CW radar systems. This work builds on that concept and formulates a system design to combine it with a UWB sensor to allow for high-resolution localization and detection of personnel in high clutter environments. The system design focuses on simultaneous operation of stepped FM and CW modes allowing for high measurement density in both operational modalities. Theory of operation and aspects of system design are presented as well as simulations detailing radar image reconstruction in through the wall and high clutter environments.

1.0 INTRODUCTION

Detection, location and identification of people and objects located behind structure walls or in collapsed rubble are current technology gaps in security, defense and disaster recovery areas. This is a particularly challenging technological problem because of the wide variance in building materials, interior structures and urbanized areas throughout the world. Similarly, making these through the wall detections and identifications at a standoff from the area under observation is desirable for security and safety reasons. A majority of the past and current research and development of this problem by the authors as well as others [1]–[3] has focused on exploiting ultra-wideband (UWB) [4] radio frequency techniques along with traditional radar methods to develop a robust see through the wall (STTW) radar system.

These methods have focused on establishing target localization through the wall by exploiting wideband probing waveforms and large aperture multi-element antenna arrays or through continuous waveforms (CW) and induced target Doppler shifts. While the UWB waveforms are able to establish precise target location inside of a structure, identifying the target as human, animal or clutter is more challenging and requires additional information. Current research and the topic of this paper centers on investigating and exploiting characteristics of

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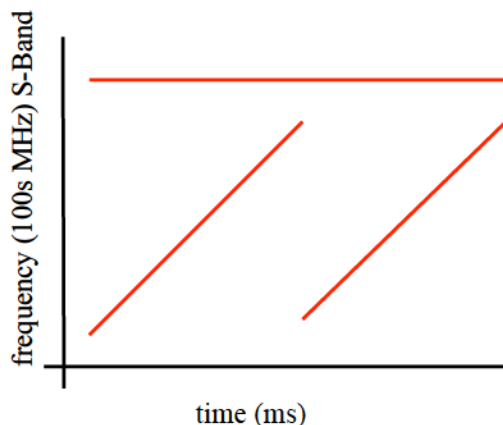
target motion and biophysical response (respiration, heartbeat, gait) and their induced micro-Doppler effect [5], [6] for use as a discriminating statistic.

Generally, frequency synthesis as well as desired pulse repetition frequencies (PRFs) of UWB frequency modulated waveforms often is in opposition with the long integration and measurement times needed to detect and leverage micro-Doppler signatures. In particular, commercially available standoff STTW systems have PRFs which are not sufficient for conventional range-Doppler [7] exploitation of cardiac signatures. Simply adjusting the PRF to meet the range-Doppler sampling requirements can have a detrimental impact on receiver sensitivity and system noise figure by decreasing integration times. To mitigate this problem, a dual-use UWB/CW MIMO waveform [8], [9] and system design is developed.

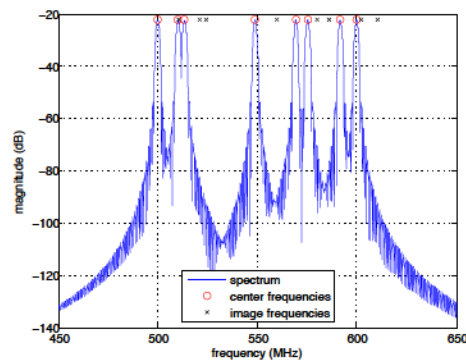
This paper details elements of the system design as well as salient points of the exploitation processing chain. Micro-Doppler effects due to biophysical responses are discussed in experimental data collected in a field environment. Similarly, waveform design and performance are detailed using field and laboratory measurements. Experimental measurements are discussed at 7-14m standoff ranges.

2.0 WAVEFORM AND SYSTEM DESIGN

A dual use UWB/CW MIMO for micro-Doppler exploitation and target localization needs to satisfy several competing requirements to optimize performance in both domains. The waveform needs to be wideband enough to provide sufficient range resolution ($\sim 0.3\text{m}$ for human targets) for discrimination between targets while having PRFs high enough to support detection of gross target motion such as walking. Directly synthesizing a high PRF, UWB, low-phase noise frequency agile waveform is a difficult design requirement to satisfy [10] and often times leads to degradation in receiver sensitivity, system signal to noise ratio (SNR) and overall performance.



(a)



(b)

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Figure 1. Dual use time-frequency waveform characteristics (a) and instantaneous spectrum of similar eight transceiver UWB MIMO radar system operating in UHF and L-bands. The frequency offset between channels allows each to independently sweep with limited self-generated interference.

As mitigation to these confounding design requirements, a multiple input multiple output (MIMO) paradigm is introduced to allow for simultaneous or multiplexed UWB and CW waveforms. Fig. 1 shows an overview of the time-frequency characteristics of the desired waveform. The shown waveform consists of two features, a linear frequency modulated ramp or series of frequency steps and a distinct frequency offset CW tone used for micro-Doppler exploitation. The waveform is designed to operate anywhere from UHF to C-band with a selectable frequency offset between the UWB component and the CW component. Fig. 1(b) shows the instantaneous spectrum of an 8-channel version of this waveform operating in UHF. As seen in the figure, the channels can be spaced as close as 700kHz apart with limited direct interference between them. For the UWB/CW waveform discussed here, the frequency offset between channels is chosen so that the third order intermodulation products appear outside of the transmission bandwidth (<1000MHz in S-band).

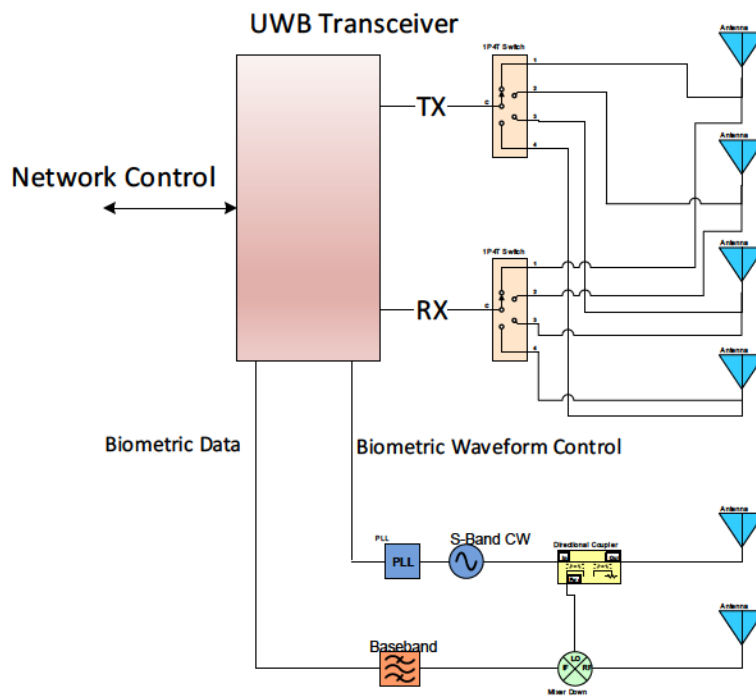


Figure 2. Block diagram of a 5-receive port MIMO transceiver of a dual UWB/CW see-through-the wall radar transceiver.

Fig. 2 shows a block diagram of a dual waveform transceiver. Here a 2-channel UWB transceiver is used to generate the probing waveform to establish target range. The probing waveform is passed through a transmit (TX) and receive (RX) switch matrix to form a four element linear antenna array. The UWB transceiver also provides control and coherent data acquisition for the biometric waveform. This element of the dual waveform

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consists of a continuously operating S-band carrier and homodyne receiver. Because of the long integration times required for high sensitivity measurements of cardiac, respiratory or gait responses through the wall, the continuous channel is preferable to sampling the UWB waveform in slow time.

3.0 RESULTS AND ANALYSIS

To show the feasibility of this technique to discriminate cardiac, respiratory and gait responses in STTW applications as well as show some limitations of using a single use UWB waveform, a series of field experiments were conducted. Data was collected using a 4-port experimental UWB transceiver operating in S-band. The majority of these experiments utilized only the UWB waveform by itself rather than the dual UWB/CW waveform. Development of the hardware support for the dual waveform is still in the conceptual stage and is not suitable for testing beyond the laboratory. However, one example showing cardiac response using a dual use waveform is shown.

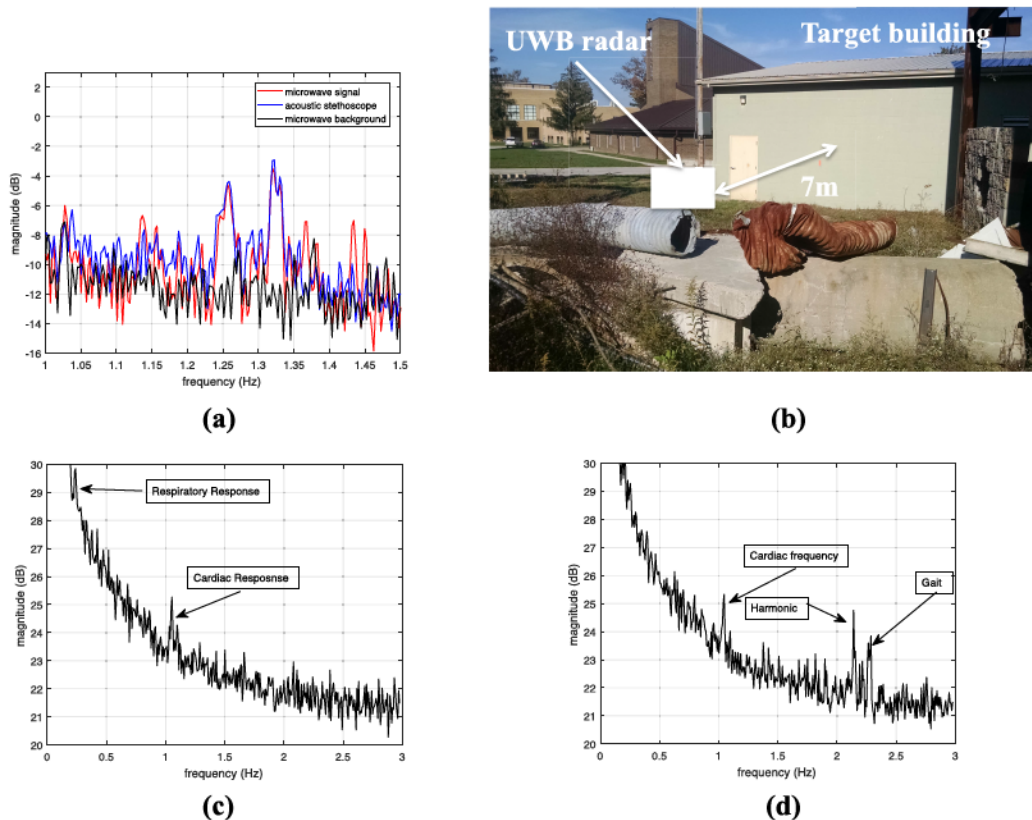


Figure 3. (a) shows a the results of a laboratory experiment for sensing cardiac response in a dual UWB/CW waveform through-the-wall (b) a photograph of a field experimental setup, (c) shows the respiratory and cardiac response of a stationary

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person in the building in (b) and (d) shows the cardiac and gait responses of a person walking a closed pattern in the building.

Fig. 3 shows the experimental results of detecting the respiratory, cardiac and gait responses in the CW and UWB radar signatures. Here, data is processed using a short time Fourier transform (Welch’s method) [11] along the slow time direction. Fig. 3(a) shows the power spectrum results of using only a CW waveform to measure the cardiac response. Here the CW transceiver is approximately 5m from a common masonry unit wall with a person sitting behind it holding their breath. Attached to the target is an electronic stethoscope, which is simultaneously sampled along with the CW receive waveform. As seen in the figure, the CW receive signal is significantly correlated with the signal from the electronic stethoscope. Notice the absence of the cardiac response in the background trace where no target is present.

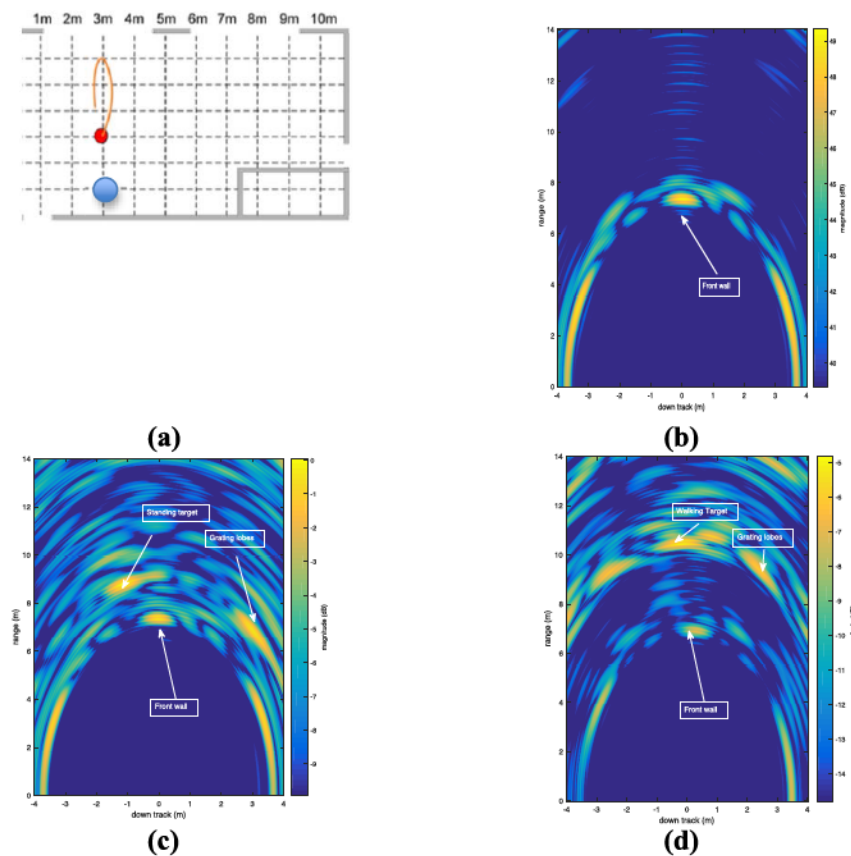


Figure 4. (a) shows the ground truth of the path walked as well as the stationary position (b) shows a 2 dimensional radar image from the 4-port UWB using no discrimination, (c) shows the image using cardiac discrimination on the stationary target and (d) shows the image using gait discrimination on the walking subject. Note that the walking position is shown as the mean position in the path.

Fig. 3(b) shows the experimental setup for the outdoor field experiments using the UWB transceiver. Here, a 4-port UWB transceiver is setup approximately 7m from a common masonry unit building. Two separate experiments were conducted inside the building, first a subject was stationary and the second the same subject walked a closed path inside the building. Fig. 3(c) shows the average power spectrum over all ports in the slow

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time direction of the stationary target. Similar to Fig. 3(a), the cardiac response is identifiable around 1Hz with the respiratory response lower, corresponding to 20 breaths/minute. Fig. 3(d) shows the average power spectrum over all ports in the slow time direction of the closed path. Here, the cardiac and gait responses seen with both shown as the mean frequency over the entire path. The gait frequency is consistent with previously published research [12] of a 40-59 year old male subject walking at a medium to fast pace. We hypothesize that the respiratory response is occluded by remnant transmitter phase noise as seen as the approximate $1/f$ frequency slope in the power spectrum as well as by additional low frequency components generated by the subject's gait.

The results shown in Fig. 3 suggest that the cardiac and gait responses are detectable through the wall when observed using the power spectrum. While this is useful information, it is desirable to be able to spatially locate the source of those responses as well as determine their frequency components. Because the UWB transceiver utilizes 4-ports to form a uniform linear antenna array, backprojected radar images can be formed. In order to exploit the responses seen in Fig. 3 a digital finite impulse response (FIR) filterbank was constructed centered on the peak cardiac and gait responses seen in Fig. 3. The receive UWB waveform is passed through this filterbank in the slow time direction and then passed to a traditional backprojection algorithm [13].

Fig. 4(b) shows the basic backprojection image formed without using the FIR filter bank. The wall is clearly visible at approximately 7m. Fig. 4(c) shows the results of the output of the filter tuned to the cardiac response. As seen in the figure, the target is clearly visible by filtering around this response. Fig. 4(d) shows the output of the gait filter. Again the response due to the gait is clearly seen. Note that while the absolute magnitude is reduced in the filtered images, the dynamic range displayed is the same between the modified and unmodified images.

The wall response is not completely suppressed using this filtering technique. This is an expected result and is due to modulation induced on wall radar signature due to both port switching and the UWB waveform itself. This is the principle reason the dual UWB/CW waveform and transceiver architecture is being developed. However, even given this limitation these results still demonstrate the feasibility of this filter bank technique to uncover both cardiac and gait information even when using a less than optimal probing waveform.

4.0 CONCLUSION

The discussion and conceptual design presented here offer a path of advancement in state of the art STTW hardware and exploitation. In particular, the combination of micro-Doppler phenomenology sensing with LFM waveforms may be of interest to researchers in the field. The results demonstrate the ability of both UWB and CW waveforms to sense and identify micro-Doppler responses in the radar receive waveforms due to humans through the wall at standoffs. Experimental results have focused on exploiting the UWB waveform only, with a system design suggested for incorporating a CW component in a MIMO architecture. Future work will focus on instantiating a field capable dual waveform system as well further work on exploitation algorithms.

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