31st Annual International Conference of the IEEE EMBS
Minneapolis, Minnesota, USA, September 2-6, 2009

Performance Assessment Techniques for Doppler Radar Physiological Sensors

Noah Hafner, Student Member, IEEE, Victor Lubecke, Senior Member, IEEE

***Abstract*—This paper presents a technique for assessing the performance of continuous wave Doppler radar systems for physiological sensing. The technique includes an artificial target for testing physiological sensing radar systems with motion analogous to human heart movement and software algorithms leveraging the capabilities of this target to simply test radar system performance. The mechanical target provides simple to complex patterns of motion that are stable and repeatable. Details of radar system performance can be assessed and the effects of configuration changes that might not appear with a human target can be observed when using this mechanical target.**

I. INTRODUCTION

Doppler radar monitoring of physiological signals was first suggested in 1975 [1]. Subsequent research has examined various uses of such monitoring for tasks including long range detection of life signs [2], the effects of target aspect on cardiopulmonary monitoring [3], and heart rate variability assessment [4]. Characterization of radar systems for these and other uses has used human subjects - while using human targets enables observation of end to end performance, isolating factors contributing [5] to or limiting [6] this performance can be difficult [7]. An effective technique to enable the characterization the effect on performance of system details is to use controllable targets to provide motion for the radar system to sense. By providing a controllable and repeatable source of motion, meaningful comparisons of performance can be made using details that would otherwise be obscured by inter test variations of a human test subject.

A. Radar Performance

For physiological sensing systems, the ultimate measure of performance is how successful it performs the task of detecting physiological data (e.g. human heart motion). This is important and so most testing involves using the radar on humans. While testing with human motion is indispensable, it is not ideal for all cases: the pattern of motion constantly changes and people have limited parameters that they can safely experience. A target able to create repeatable patterns of motion with lessened constraints would enable testing of small adjustments in radar systems that may be obscured by the variation in motion when using human subjects to test these radar systems. This target could augment testing with human targets by providing complimentary coverage to enable better understanding of the radar performance.

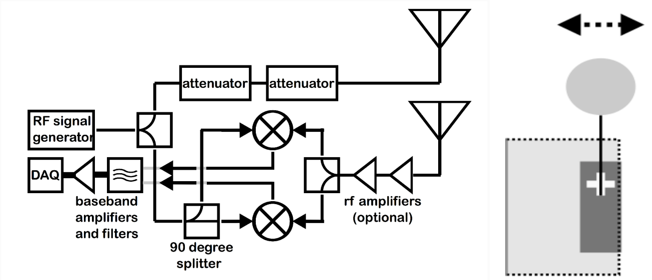

Fig 1: Diagram of Doppler radar with mechanical radar target used for assessing the capabilities of the radar system. The target provides a pattern of motion similar to that of a human heart to be measured by the radar.

B. Issues affecting performance

A Doppler radar system detects motion by transmitting a specific at frequency and then determining the doppler shift in the reflected signal. The direct conversion radar system used here accomplishes this by using a single local oscillator (LO) for the transmitting and receiving portions of the radar. The received signal is mixed with the LO directly converting the signal to baseband.

For small, slow targets with constantly varying speed, various effects can reduce accuracy: phase noise, electrical noise, rf interference and clutter from other motion. System variations to mitigate these effects may, individually provide some benefit, but not enough to provide noticeable changes in overall performance with human targets.

C. Performance assessment with human targets

Radars for human measurement are often tested using people. This has the benefit of directly testing actual performance and no special effort is required to generate the motion. Some of the problems with using human generated motion for assessing performance or characterizing these

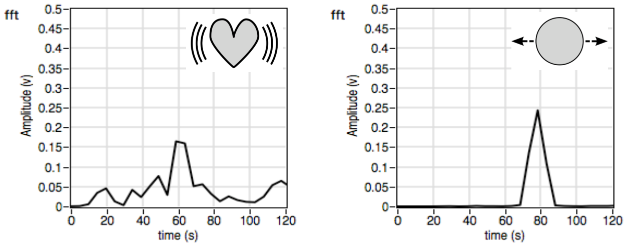

Fig 2: Frequency domain plots for human and mechanical motion at 1m. Even with lung motion filtered out, the heart shows variation in rate during the 12s fft window in addition to extraneous motion at other frequencies in the band of interest. The mechanical target demonstrates a high degree of repeatability (constant single frequency in motion pattern) and can be easily reprogrammed with a more complex pattern to create a higher fidelity copy of the motion a human heart produces.

Manuscript received April 7, 2009. This work was supported in part by the National Science Foundation under Grant ECS0702234.

Noah Hafner is with the Electrical Engineering Department, University of Hawaii, Honolulu, HI 96822 USA (e-mail: nmh+ieee@nomh.org).

Victor M. Lubecke is with the Electrical Engineering Department, University of Hawaii, Honolulu, HI 96822 USA and Kai Sensors, Honolulu, HI 96822 USA (e-mail: lubecke@ieee.org).

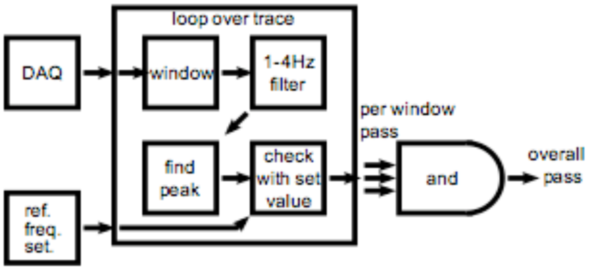

Fig 3: Motion detection and grading algorithm. The logic that creates the pass/fail indicator requires a signal to correctly match the frequency programmed into the target for all positions of the window as moves over the trace.

systems include: uncontrolled motion, reference measurements, variation between tests (and during tests), variation between individuals, excess motion clutter and limits on the possible motion. A simple example of this is separately generating motion with heart or lungs – stopping a person's heart is dangerous, and certainly not something to do when there exist alternatives. A more interesting example is the extraneous motion that people create. In addition to cardiopulmonary motions, people have minute motion in various parts of their bodies – these movements are small compared to visible motions (walking, breathing), but are large enough to interfere with experiments to characterize small differences in measurement technique.

D. Performance assessment with mechanical targets

Using a simple mechanical target for testing radar systems can provide improved control for motion – eliminating some variations between experiments. The largest drawback for using non-human targets for assessing performance on humans is assuring correspondence between the two. The more obvious differences include: rhythm of motion, waveform shape of the motion, size of target, reflective characteristics of target. Since humans show variation between individuals, a mechanical target cannot both provide the same characteristics and match multiple people equally well. Using mechanical targets can be seen instead as offering complimentary capabilities that allow testing of performance in ways that human targets do not.

II. TEST SETUP

A. Radar

The radar was assembled using coaxial components: E4433B RF signal generator, Mini-Circuits ZFSC-2-2500 splitters, Mini-Circuits ZFM-4212+ mixers, Narda 4033C hybrid splitter, Laird Technologies PA24-16 16 dBi panel antennas, ZX60-6013E-S, SRS SR560 amplifiers, and a NI USB-6009 data acquisition card.

The attenuators were used to reduce the transmitted power by up to 60dB. Since the RF signal generator was set to 13dBm, the resultant transmit powers (after one 3dB splitter and the two attenuators) ranged between 10dBm and -50dBm (10mW to 10nW). For longer range tests (20m and greater), rf amplifiers were optionally used. These amplifiers have a maximum output power of little more than 13dBm and were therefore connected on the receive side where they could each provide almost 15dB of gain.

B. Target

The mechanical target used was created with a 5cm diameter spherical reflector on a pivoting arm. The arm was mounted directly to the output shaft of a small servo, controlled and powered by a simple microcontroller. During experiments, the target was placed on a second cart so its height would match that of the radar antennas and additionally to enable easy adjustment of radar-target distance.

The only portions of the mechanical target that move with the same pattern of motion as the reflector are the arm, the screws mounting the arm to the servo and the servo horn that connected to the shaft. The arm was made from 3mm thick plastic, to reduce radar reflections from it. The screws were small compared to the wavelength (125mm >> 1.5mm) and moved much less than the reflector. As Fig 3 shows, for small angular displacements, the motion can be considered essentially linear (along the tangent to a circle centered on the axis of rotation). For larger motions, this no longer holds. The motion desired from the targets is limited to 10mm peak to peak, so the reflector was positioned 70mm from the axis so that the target would be at most 0.2mm from the ideal straight line position.

C. Environment

The testing was conducted in a building hallway to allow for greater radar-target ranges. The only special consideration for using the hallway was arranging to test the radar early in the morning when the building was empty to reduce clutter from people walking in the hall. The 2.4 GHz radios (802.11) present were left on and operating during the testing.

The target was positioned 1, 5, 10, 15, 20, and 30 meters from the radar and moved in a sinusoidal motion at 1.3 Hz with a 10mm and then a 1mm range of motion.

D. Performance Assessment

For these tests the radar (including motion detection software) was considered to have successfully detected the motion of the target if the reported frequency of motion matched that programmed into the target. Correctly detecting the motion using the in phase or the quadrature phase channel was considered sufficient.

The motion detection portion of the software performed

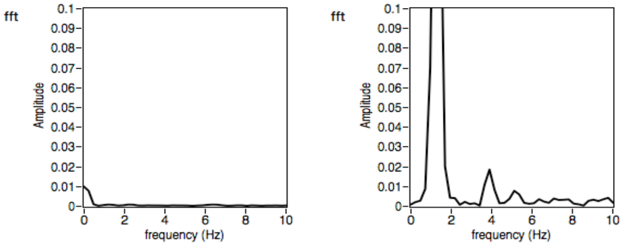

Fig 4: Frequency domain plots of the radar I channel with the target stationary and then moving. The plot with no motion shows a low noise floor. [edit: close]

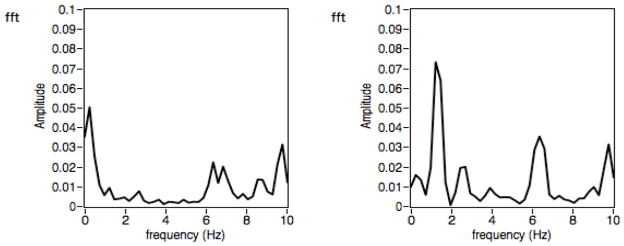

Fig 5: Received signals for 30m tests. The first plot shows environmental noise with no target motion while the second plot shows the easily detectable signal from the moving target.

frequency domain analysis of the signals in four second blocks by searching in the 1-4Hz (60-240bpm) range and selecting the frequency bin with the highest energy.

The assessment portion of the software checked for a match between the selected frequency with the specified frequency of motion – anything other than the two matching (same frequency bin) was counted as a failure.

III. Test Results

A. Short range (1m)

The short range test results show the correspondence between the signal produced as a result of human heart motion and that produced from the mechanical target. Fig. 2 shows the radar output for a human (heart and lung motion) and additionally the radar output for a mechanical target. Fig. 4 Shows the fft from the I channel from the radar with the mechanical target at 1m.

B. Long range (30m)

At longer ranges, the radar signals showed artifacts from the interference caused by the 802.11 network in addition to the lower signal levels expected at these ranges. Though these artifacts can be clearly seen in Fig. 5, the radar is still able to correctly detect the motion of the target. The spikes in the frequency plot at 3.5, 6.1, 8.5 and 9.8Hz are not harmonics of the target motion (1.3Hz) but rather other rf energy (nearby 802.11 equipment).

C. Detection

The detection algorithm was checked for false positive results by sequentially setting the frequency of interest to an other value as well as setting the target at a different rate.

While the detection algorithm provided stable (and correct) results when tested with a moving target, control tests (with no target motion) resulted in various incorrectly detected frequencies that changed within each test as well as between successive tests. Generally, the ``detected motion'' had little relation to that programmed into the target (since the target was switched off). Most tests used a single frequency of motion – 78bpm (1.3Hz), but the detection algorithm also correctly detected the frequency of motion when the target was programmed for 0.3Hz as well as other values in the 1-4Hz range.

Table 1: Output from motion detection grading module. -50dBm transmit power was only tested at 30m with two amplifiers.

	transmit power (dBm)		
Range (m)	10	-30	-50
1	pass	pass	-
10	pass	pass	-
20	pass	pass	-
20 w/amp	pass	x	-
30 w/amp	pass	x	-

IV. Discussion

The three tests presented include one comparing the radar response to a human target and the response to a mechanical target, one showing the the radar response for a close target and one showing the response of the radar for a far target.

Even with directional antennas, the radar was sensitive to nearby movement. This was not a problem for tests with the target located close to the radar but long range tests resulted in low return power from the target and showed much more sensitivity to extraneous motion. To prevent non-target motion from interfering with the radar, a short timer was used to delay the start of test until after people moved away from the radar.

The long range test, which used rf amplifiers in the receive section, showed significant noise before the target started moving. The signal generated by the motion of the target is easily greater than that of the noise in the frequency range of interset, but for some of the lower transmit power tests, the noise at 6.5Hz and 10Hz was greater than the signal from the target. In these cases the brick wall filter at 4Hz allowed the motion detection algorithm to correctly identify the target motion, despite this noise. The noise seen in tests with lower return power (low transmit power, long range or both) had a similar appearance to what an idle 802.11 network might produce (10Hz beacon).

This is significant for a direct conversion doppler radar system since the range correlation effect lessens as range increases [5].

V. Conclusion

This paper presents an artificial target for testing physiological sensing radar systems, demonstrates motion analogous to human heart movement, introduces software algorithms leveraging the capabilities of this target to simply test radar system performance and shows experimental results using this test setup to investigate how increasing radar-target range affects system performance.

References

[1] J.C. Lin, "Non-invasive microwave measurement of respiration," Proceedings of the IEEE, vol. 63, pp. 1530,Oct. 1975.

[2] K.-M. Chen, D. Misra, H. Wang, H.-R. Chuang, E. Postow, "An X-Band Microwave Life-Detection System," IEEE Transactions on Biomedical Engineering, vol. BME-33, NO. 7, July 1986

[3] Changzhi Li; Jenshan Lin; Yanming Xiao, "Robust Overnight Monitoring of Human Vital Signs by a Non-contact Respiration and Heartbeat Detector," Engineering in Medicine and Biology Society,

2006. EMBS '06. 28th Annual International Conference of the IEEE , vol., no., pp.2235-2238, Aug. 30 2006-Sept. 3 2006

[4] Boric-Lubecke, O.; Massagram, W.; Lubecke, V.M.; Host-Madsen, A.; Jokanovic, B., "Heart Rate Variability Assessment Using Doppler Radar with Linear Demodulation," Microwave Conference, 2008. EuMC 2008. 38th European , vol., no., pp.420-423, 27-31 Oct. 2008

[5] Droitcour, A.D.; Boric-Lubecke, O.; Lubecke, V.M.; Lin, J.; Kovacs, G.T.A., "Range correlation and I/Q performance benefits in single chip silicon Doppler radars for noncontact cardiopulmonary monitoring," Microwave Theory and Techniques, IEEE Transactions on , vol.52, no.3, pp. 838-848, March 2004

[6] B.-K. Park, S. Yamada, V. M. Lubecke, and 0. Boric-Lubecke, "Single-channel receiver limitations in Doppler radar measurements of periodic motion" IEEE Radio and Wireless Symp., San Diego, CA, USA, pp. 99-102, 2006.

[7] S. Yamada, M. Chen, and V. Lubecke, “Sub-uW signal power doppler radar heart rate detection,” Microwave Conference, 2006, APMC 2006, Asia-Pacific, pp. 51-54, Dec. 2006.

[8] Droitcour, A.D.; Boric-Lubecke, O.; Kovacs, G.T.A., "Signal to Noise Ratio in Dopper Radar System for Heart and Respiratory Rate Measurements,” MTT, 2006