Radar Based Automatic Target System

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***Abstract*— This paper describes the novel application of both dual tone CW and ISAR techniques to measure the position of a small high velocity projectile as it passes through a defined sensory virtual plane, so forming the basis of an automatic targeting system for live fire training. Simulation and initial experimental results are presented, as well as a general description of the system.**

I. Introduction

A marksman training in the modern firing range is typically assessed using an automated electronic version of the traditional paper target. Such systems can offer greater accuracy and the opportunity to perform shot analysis to determine the ability of a marksman or to calibrate a firearm. Automatic targets operate by establishing a sensory area known as the virtual plane in which the system is able to measure the coordinates of a projectile as it passes through this zone. Systems that are commercially available operate using either acoustic or optical principles. In the case of optical systems an array of photo-emitters and photo-detectors are employed for the two axes of measurement, and so resolution is dependant upon sensor density. Acoustic systems rely on the conical shockwave of the passing bullet, and so can only measure accurately supersonic projectiles. Also any distortion of the shock-cone shape due to pressure variations, or even wind, can greatly effect their operation, and so these systems are limited to indoor use. Optical systems do not have these restrictions, however they are complicated in construction and have a large physical presence, making them susceptible to damage from stray shots, and difficult to install. The various technical problems associated with optical and acoustic automatic target systems has made the development of a radar based system desirable, as such a system will generally be more compact, capable of measuring both subsonic and supersonic velocity projectiles, and less influenced by the characteristics of the local environment. There are certain specific requirements set out for the development of such a system, which includes low production cost that results in the need for a simple design, and a desired accuracy of half-calibre (2mm approx.). Also, there is interest in the development of an artillery version that can be used to detect the shot position of shells. This paper describes the work so far in developing a radar based targeting system for small arms fire.

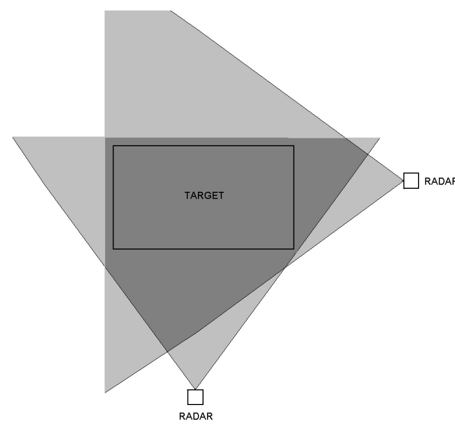

Fig. 1. General arrangement for the radar based automatic target system.

II. General Concept

The general concept for the radar based automatic target is shown in figure 1, where it can be seen that the virtual plane is formed by the boresights of two overlapping radar beams, one measuring range along the x-axis, and the other along the y-axis, so giving the two dimensional coordinates of a passing projectile. The actual deployment of the radars is that they would be positioned at ground level, underneath the target zone; one looking upwards and $45°$ left, the other upwards $45°$ right. In this way ground clutter returns are minimized, as would be the mutual interference of similar systems operating on neighboring firing lanes.

While a varied number of techniques may be used in the actual measurement of range, a requirement set out for this work is that the technology must have a low production cost. Based on this requirement, rather than employing a modulated carrier, a CW (continuous wave) system has been developed, and hence range measurements will be made by virtue of the phase rotation of a propagating electromagnetic wave. However the phase of such a carrier will rotate through 2π radians every $\lambda/2$ metres of range, so resulting in an ambiguous measurement of projectile's position in space. For the distances of interest ($> 1m$), and the carrier frequencies under

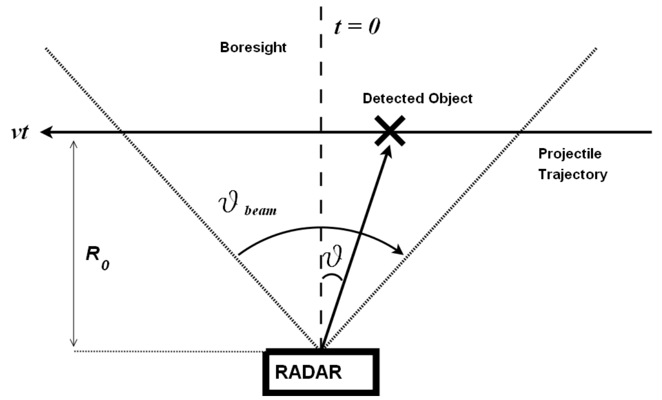

Fig. 2. The cross range trajectory of a projectile passing through the virtual plane

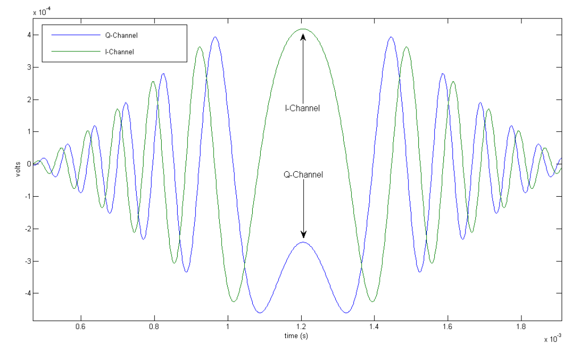

Fig. 3. The I and Q baseband waveforms associated with a single carrier detecting the passage of a projectile.

consideration ($> 1GHz$), this places a severe limitation on this general principle. A technique is discussed within the literature that can be employed to increase this maximum unambiguous range, so that wavelengths of only a few centimetres may be used to measure ranges of several metres [1]–[4]. The technique involves employing two carriers closely spaced in frequency, such that the maximum unambiguous range is set by the difference in frequency, as shown in (2). Range is then determined from the phase difference of these two carriers, as shown in (1):

$$r = \frac{c}{4\pi \left(f_2 - f_1\right)} \left(\phi_2 - \phi_1\right) \tag{1}$$

Where f_1 and f_2 are the two carrier frequencies, while ϕ_1 and ϕ_1 are the respective bistatic phase shifts. Hence the maximum unambiguous range associated with this technique is given by (2):

$$R_u = \frac{c}{2\left(f_2 - f_1\right)} \tag{2}$$

This technique has been described in the literature for various applications, some of which are related to ballistics [2], while others have been directed to entirely different areas [1], [3], [4]. However the application under consideration here is believed to be entirely novel.

As the projectile passes through the virtual plane it can be seen from figure 2 that the trajectory will be cross-range relative to the two radars.

While the projectile travels along it's trajectory the range varies as a function of time, hence from simple trigonometry the instantaneous phase shift of the carrier at time t, for a projectile traveling at velocity v, along a straight trajectory at right angles to the boresight is given by (3):

$$\phi\left(t\right) = \frac{4\pi {R_0}^2}{\lambda v t} \tag{3}$$

Where R_0 is the range of the projectile when it reaches the boresight of the radar. This expression assumes that the maximum azimuth angle in which the projectile is detected does not exceed $+/-10°$, otherwise the relationship becomes non-linear, as apparent projectile velocity is directly proportional to the sine of the broadside or azimuth angle (ϑ). This window can be applied by either a suitable antenna beam shape, or more practically through a filtering action provided by the signal processing software. As the projectile travels along its trajectory the Doppler of the returned carrier changes in sympathy with the azimuth angle relative to the antenna, this can bee seen in (3), where the instantaneous Doppler frequency $f_d\left(\vartheta\right)$ is a function of the instantaneous azimuth angle (ϑ).

$$f_d\left(\vartheta\right) = \frac{2v}{\lambda} \sin\left(\vartheta\right) \tag{4}$$

From this the maximum Doppler frequency before non-linear effects become apparent $f_{d(\max)}$, for a given carrier wavelength λ and projectile velocity v, can be found by setting the instantaneous azimuth angle to $10°$, this is shown in (5):

$$f_{d(\max)} = \frac{v}{2.88\lambda} \tag{5}$$

This range measuring technique is in fact an application of ISAR (Inverse Synthetic Aperture Radar), as it results in a varying Doppler in sympathy with the projectile's progresses through it's trajectory. This can be seen in figure 3, which shows the simulated baseband waveforms associated with a single 10GHz carrier detecting a 1000 m/s projectile traveling cross-range, where R_0 (see figure 2) is 2m.

The two waveforms represent the I and Q channels required to extract phase information from the returned carrier by employing quadrature detection, so resulting in the two baseband signals. As explained earlier, two such carriers must be used to extend the unambiguous range of the system, and so for a single axis of measurement a total of four baseband waveforms need to be processed. For the complete system, that measures the two dimensional coordinates of a passing projectile, altogether eight waveforms are processed simultaneously for a single shot. As can be seen from figure 3 as the projectile follows it's trajectory the frequency of the baseband signal decreases, before crossing the line of sight (boresight), at which point the phase of the signal reverses, before increasing in frequency again. It is at this point of phase inversion where the range of the projectile, as it passes through the virtual plane, is measured, and so a coordinate reading is taken. Specifically the system records the Doppler history of the projectiles passage through the radar beam, so that when an FFT (Fast Fourier Transform) is performed on the complex signal composed of the I and Q channels, phase-frequency data for the two individual carriers are found. The algorithm then finds the associated range from this captured data by application of (1).

III. Simulations

Initially several simulations were conducted, written in MATLAB, to determine the accuracy of the described technique in measuring the range along a single axis. There were primarily two areas of interest, the first was to determine the accuracy of the technique/algorithm with varying projectile trajectories, and the second was to evaluate the systems accuracy in the presence of gaussian noise.

A. Effect of Projectile Trajectory

So as to determine the effect of range and trajectory gradient (i.e. the angle of the projectile path with respect to the perpendicular of the radar boresight), on the accuracy of the technique, a 10,000 shot simulation was run, each shot having a different miss-distance (uniformly distributed over -0.5m to 0.5m) and trajectory gradient (uniformly distributed over -0.2 to 0.2). Here miss-distance refers to the distance from the center of the virtual target to the point at which the projectile passes through this detection area. This center point is located at some fixed range from the radar, and in this particular simulation it was set at -2m, i.e. the radar antenna is located 2m to the left from the center of the virtual plane from the perspective of the marksman. Hence the position of where a projectile has passed through the detection area can be located with cartesian coordinates, where the origin is at the center of the virtual plane, and not the position of the radar. The results of this simulation are shown graphically in figure 4, where the error in measured miss-distance is given in metres, and is shown to be predominantly a function of trajectory gradient. However this is due to the fact that with increasing gradient, the point of closest approach and the line of sight of the antenna, or boresight, become increasingly misaligned. This error is therefore predictable, and can be accurately calculated with simple geometry.

In practice the greatest miss-distance and trajectory gradient in a small-arms firing range is approximately 0.3m and 0.024 respectively, and from simulation data, as represented in figure 4, this equates to an error of less than 35.6×10^{-6}m.

B. Immunity to Gaussian Noise

In any system there is the inherent problem of noise, and so it is important to determine what level of noise will degrade the performance of the proposed system. In a 5,000 shot simulation, where gaussian noise is added to the baseband signal from the simulated I and Q channels, the effect on miss-distance accuracy is found for a range (10dB to 50dB) of signal to noise ratios (SNR). Each SNR value is assessed with 10 shots so as to build-up a set of data from which the mean error and standard deviation can be found. The results of this simulation are given in table I. From this data it can be seen that system accuracy is maintained at an SNR of 40dB or more, and so this sets a requirement for the practical realization of this technique.

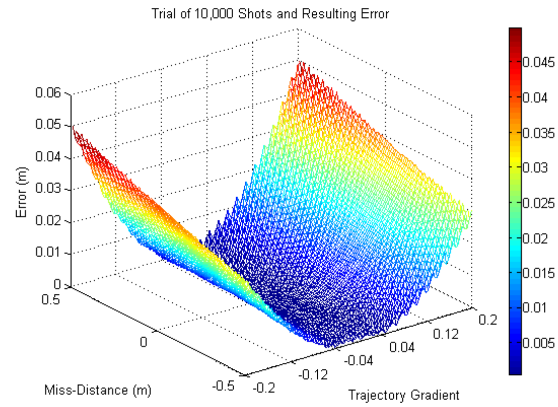

Fig. 4. Simulated shots of varying miss-distance and trajectory gradient

TABLE I

SNR data from simulation, showing the effect on system accuracy.

SNR (dB)	Mean Error (m)	Standard Deviation (m)
10	4×10^{-3}	21.2×10^{-3}
20	501.3×10^{-6}	4.8×10^{-3}
30	390×10^{-6}	1.4×10^{-3}
40	196.3×10^{-6}	482.6×10^{-6}
50	260×10^{-6}	150.3×10^{-6}

IV. Practical Results

For the purpose of testing the practical application of this technique a 2GHz dual-carrier (2GHz and 2.05GHz) radar system, employing quadrature detection, was built using commercially available modular units, and initial testing has resulted in capturing waveforms of a 830m/s velocity 7.62mm NATO (51mm) bullet . Figure 5 shows the typical baseband I and Q channel waveforms associated with one of the carriers, and when compared with figure 3 it can be seen how this bares a close relation to the waveform derived from simulations. This observation supports the validity of the simulation work, and the next stage will be the testing of the systems range measuring ability, and hence the principle behind the automatic target technology.

V. Conclusion

Dual-carrier radar systems employing quadrature detection to measure phase, designed to capture the Doppler history of a

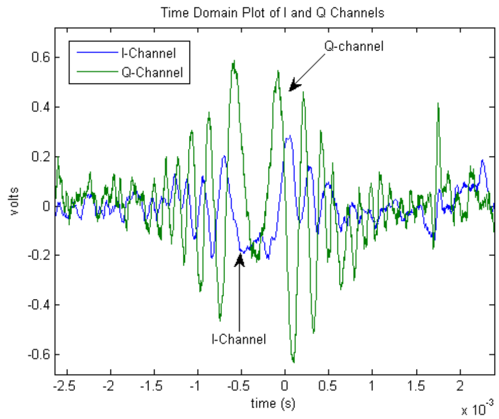

Fig. 5. I and Q channels from the 2GHz practical system.

cross-range projectile, provides a novel and economic solution to measuring the point of passage of a projectile through a defined area, or virtual plane. Simulations have shown that such a technique is effective in measuring the range of a projectile to an accuracy well within the half-calibre specification. Practical investigations to date, using a 2GHz system, have indicated that the waveforms from the simulations resemble closely those captured by the radar during live-fire trials. Based on this, the next step will be to test the systems ability to measure range accurately. Also, as an extension of the development of the automatic target, it has been suggested that it may be possible to detect and measure the micro-dynamics of an airborne projectile by virtue of micro-Doppler. Bullets characteristically have a variety of different motions, which include spin, yaw, gyration and nutation. These micro-motions result in the generation of frequency sidebands about the main cross-range Doppler signal, and are of interest not only because of the potential effect on the system accuracy, but also as a new aspect of the general technology that could be employed in ballistics research.

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