A Chaos Based Waveform Approach to Radar Target Identification

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Abstract—We present a low resolution method for radar target identification. The method employs optimized waveforms in cross correlation with the return from a low frequency chirp to distinguish between similar candidate targets. Target signature waveforms were generated every degree in azimuth for generic wing-body-tail targets using FDTD simulation. The targets were four to five meters in length with approximately two meter wing spans. The transmitted linear chirp had a 20% band width and 250 MHz center frequency. We generated candidate waveforms using a simple chaotic map to cross correlate with the target returns. The waveforms were generated by passing chaotic time series through a bandpass filter. Alternately the waveforms were constructed by concatenating constant amplitude sinusoids whose periods were specified by the amplitudes of the chaotic time series. In both cases waveforms were constructed with the same bandwidth and center frequency as the transmitted chirp. A large number of test waveforms were generated by random variation of the generating chaotic map parameters. These test waveforms were cross correlated with the return waveforms from two similar targets. Waveforms that maximized (minimized) the cross correlation amplitude ratio difference between targets were retained and fine tuned with simplex optimization. Optimization was conducted over target azimuthal windows up to 10° in width. Best maximizing and minimizing test waveforms were retained for each data window. Using this method pairwise discrimination between candidate targets could be achieved over most aspects where the signature of the respective targets are not varying too rapidly with angle.

1. INTRODUCTION

The problem of identifying targets seen in radar returns has important civilian and military applications. The current methods seek to identify a particular complex target by resolution of individual scatterers [1] or by recognizing characteristic resonances [2, 3]. Here we set out to devise a method that will distinguish between two candidate known targets, \( A \) and \( B \) by generating and optimizing waveforms to cross correlate with their known simulated or measured radar returns [4, 5]. With the advent of modern fast gigahertz electronics complex real time radar signals can be readily constructed, digitized and processed. In principal these waveforms can be fabricated to enhance or null the signature of a single known target from detailed knowledge of its geometry and surface properties. Constructing waveforms that will simultaneously maximize (minimize) the radar return from one target while simultaneously minimizing (maximizing) the return from a second target is considerably more difficult. We use chaos based waveform optimization to perform this task. Employing an appropriate chaotic map allows us to generate a very wide variety of deterministic reproducible waveforms from random variation of a few parameters. We select and optimize these test waveforms by cross correlation with the simulated or measured return of fast radar chirps reflected from two known targets at multiple angles of incidence. With our optimized waveforms we can form ratios of cross correlations of the two targets with both maximizing and minimizing chaos based test waveforms. We then use the difference between cross correlation ratios to discriminate between the targets.

2. METHOD

In this work, we assume that the radar transmitted pulse is a simple linear chirp, \( \Psi_{\text{chirp}} \), transmitted with a (20%) bandwidth. The transmitted pulse could be any waveform with sufficient bandwidth but we simplify the problem by limiting it to a fast linear chirp. In this paper, we also assume, for convenience, that the target of interest is in level flight at a substantial distance and is monitored by a mono-static radar. We assume that in practice standard radar tracking will provide Doppler correction and angle of approach information.

We also assume that the radiation patterns returned from the two known complex scatterers, \( \Psi^A \), \( \Psi^B \) are normalized to the average amplitude of the return and are faithfully digitized. Radar
range data (or simulations) for each target are collected at multiple azimuthal angles $\Theta$ as individual targets are rotated in the far field. We also assume that the returned waveforms vary slowly with azimuth. Since in practice the angle of approach information is approximate, a number of waveforms within an azimuthal window are analyzed together.

We wish then to find a waveform for each azimuthal data window, $\Phi_{\text{max}}^{A|B}$, that will maximize the averaged cross correlation amplitude, $\langle |R(\Phi_{\text{max}}^{A|B}\Psi^A)| \rangle$ with return from target $A$ while minimizing the the cross correlation amplitude with target $B$, $\langle |R(\Phi_{\text{max}}^{A|B}\Psi^B)| \rangle$. Also we wish to find another waveform, $\Phi_{\text{min}}^{A|B}$, that will minimize $\langle |R(\Phi_{\text{min}}^{A|B}\Psi^A)| \rangle$ while maximizing $\langle |R(\Phi_{\text{min}}^{A|B}\Psi^B)| \rangle$. Taking the ratios of the maximizing to minimizing cross correlations for each target defines their respective characteristic contrast ratio in the angular window of interest. The difference in these contrast ratios is used to distinguish between targets.

We have constructed the trial waveforms, $\Phi$, by two methods; 1) the concatenation of single unit amplitude sinusoids whose periods are specified by a chaotic time series and 2) band pass filtering of a chaotic time series. In both cases the time series was constructed by evaluating the modulus of an iterated six parameter analog shift register sum [4, 5]. The resulting chaotic time series is a sequence of floating point values bounded in value between 0 and 1. In the first instance, the time series is mapped onto sinusoids with periods within the desired band width and center frequency. In the second case the center frequency and bandwidth of the band pass filter are similarly specified. In both cases we require that the center frequency and bandwidth match that of the transmitted chirp, $\Psi_{\text{chirp}}$. In the first case we further required that the test waveform conform to the same number as sinusoidal elements present $\Psi_{\text{chirp}}$. In the second case we required that the test waveform conform to the length of the identically windowed return waveforms from the two targets, $\Psi^A$ and $\Psi^B$.

For simplicity we first consider the process of finding $\Phi$ at a single azimuth. In practice we iterate to a solution first composing a random chaos based test waveform. Then compute the cross correlation amplitude with the waveforms $\Psi^A$ and $\Psi^B$ returned from both targets $A$ and $B$ at the angle of interest, We then compare amplitudes to previous iterations our best $\Phi_{\text{max}}^{A|B}$ and $\Phi_{\text{min}}^{A|B}$. If the new waveform maximizes the correlation ratios when substituted for the previous best $\Phi_{\text{max}}^{A|B}$ or $\Phi_{\text{min}}^{A|B}$ it is retained. The three ratios to be maximized are summed in Eq. (1).

\[
G = \frac{\langle |R(\Phi_{\text{max}}^{A|B}\Psi^A)| \rangle}{\langle |R(\Phi_{\text{min}}^{A|B}\Psi^A)| \rangle} + \frac{\langle |R(\Phi_{\text{max}}^{A|B}\Psi^B)| \rangle}{\langle |R(\Phi_{\text{min}}^{A|B}\Psi^B)| \rangle} + \frac{\langle |R(\Phi_{\text{min}}^{A|B}\Psi^B)| \rangle}{\langle |R(\Phi_{\text{min}}^{A|B}\Psi^A)| \rangle}
\]  

(1)

We in fact calculate our ratio comparisons over a number of azimuthal angles contained in a window. This is necessary since the angle of approach is only approximately known. While computationally more complex this is a straightforward extension of the single angle process.

The process is repeated many times. After this iteration process is complete the two best test waveforms, $\Phi_{\text{max}}^{A|B}$ and $\Phi_{\text{min}}^{A|B}$, generated in each azimuthal window are then optimized using the down hill simplex amoeba optimization routine [6]. In the same process waveforms $\Phi_{\text{max}}^{B|A}$ and $\Phi_{\text{min}}^{B|A}$ are also generated selecting target $B$ over $A$. Due to the nature of the selection process $\Phi_{\text{max}}^{A|B} \neq \Phi_{\text{min}}^{B|A}$ and $\Phi_{\text{min}}^{A|B} \neq \Phi_{\text{max}}^{B|A}$. We then distinguish target $A$ from target $B$ by computing the contrast $C_i^{A|B}$ and contrast difference $D_i^{A|B}$ in each azimuthal window centered at $\Theta_i$,

\[
C_i^{A|B}(A, \Theta) = 20 \log_{10} \left( \frac{\langle |R(\Phi_{\text{max}}^{A|B}(i)\Psi^A(\Theta))| \rangle}{\langle |R(\Phi_{\text{min}}^{A|B}(i)\Psi^A(\Theta))| \rangle} \right) 
\]

(2)

\[
C_i^{A|B}(B, \Theta) = 20 \log_{10} \left( \frac{\langle |R(\Phi_{\text{max}}^{A|B}(i)\Psi^B(\Theta))| \rangle}{\langle |R(\Phi_{\text{min}}^{A|B}(i)\Psi^B(\Theta))| \rangle} \right) 
\]

(3)

\[
D_i^{A|B}(\Theta) = 20 \log_{10} \left( \frac{\langle |R(\Phi_{\text{max}}^{A|B}(i)\Psi^A(\Theta))| \rangle/\langle |R(\Phi_{\text{min}}^{A|B}(i)\Psi^A(\Theta))| \rangle}{\langle |R(\Phi_{\text{max}}^{A|B}(i)\Psi^B(\Theta))| \rangle/\langle |R(\Phi_{\text{min}}^{A|B}(i)\Psi^B(\Theta))| \rangle} \right) 
\]

(4)

As part of the same process we can save chaos based waveforms $\Phi_{\text{max}}^{A}$ and $\Phi_{\text{min}}^{A}$ which maximize the contrasts $C_i^{A}$ and $C_i^{B}$ in window $i$,

\[
C_i^{A}(\Theta) = 20 \log_{10} \left( \frac{\langle |R(\Phi_{\text{max}}^{A}(i)\Psi^A(\Theta))| \rangle}{\langle |R(\Phi_{\text{min}}^{A}(i)\Psi^A(\Theta))| \rangle} \right) 
\]

(5)

\[
C_i^{B}(\Theta) = 20 \log_{10} \left( \frac{\langle |R(\Phi_{\text{max}}^{B}(i)\Psi^B(\Theta))| \rangle}{\langle |R(\Phi_{\text{min}}^{B}(i)\Psi^B(\Theta))| \rangle} \right) 
\]

(6)
A large contrast $C_A$ does not necessarily select target $A$ itself but when used in combination with the $C_{A|B}^{AB}$ and $D_{A|B}^{AB}$ will serve to confirm that the identification of target $A$. Thus in order to distinguish $A$ from $B$, we save the parameters used to generate $\Phi_{A|B}^{\max}$ and $\Phi_{A|B}^{\max}$ and, if desired, $\Phi_{A|B}^{\max}$ and $\Phi_{A|B}^{\min}$ for each angular window using the same chaotic map and generation procedure. With fast parallel computation the contrasts and contrast differences can be rapidly generated for a large number of target combinations.

3. EXAMPLE

In order to test this scheme we created computer models of several similar generic wing/body/tail objects approximately five meters in length with features like engine ducts and radomes. The two of the target models considered here are shown in Fig. 1. Target 14 is 4.9 m long and target 16 is 4.8 m long. Both are two meters wide at the wings. None of the models simulate real military or civilian targets. The models are all right-left symmetric and have enough complexity to scramble the transmitted pulse upon reflection. We used a finite difference time domain (FDTD) code to launch linear chirps at the models at various angles (one degree steps between $0^\circ$ and $180^\circ$). The short chirp had 50 MHz (20\%) band width centered at 250 MHz. The low frequency and bandwidth were chosen to slow the angular variation of the returned waveforms while still imparting enough complexity to the waveforms to enable us to distinguish between targets. The same chirp was employed for each model simulation. A mono-static far field return waveform was calculated at each angle. Care was taken to terminate the simulations before the build-up of rounding errors invalidated the return signal. FDTD error constraints limited our available target size and chirp waveform length. We split the data into overlapping ten degree wide azimuthal windows taken five degrees apart.

The transmitted chirp was constructed by concatenating thirty three individual unit amplitude sinusoids spanning 225 to 275 MHz. The optimization code calculated and compared chaos based test waveforms, $\Phi$, in cross correlation with all $\Psi_{A}(\Theta)$ and $\Psi_{B}(\Theta)$, at all angles $\Theta$ to find the best, $\Phi_{A|B}^{\max}(i)$ and $\Phi_{A|B}^{\min}(i)$ for all windows $i$.

Figure 1: Shown are the two targets studied in this paper, targets 14 and 16. The gridding was selected to be less than one twentieth of a wavelength at 275 MHz. Gold or orange indicates metal and green indicates radome. Both are approximately 5 m in length.

Figure 2: Cross correlation amplitudes for targets 16 and 14. Waveforms $\Phi_{16|14}^{\max}$ and $\Phi_{16|14}^{\min}$ optimized for a 10$^\circ$ window centered at 10$^\circ$ azimuth, 0$^\circ$ elevation. (See arrow). The cross correlations with returned waveforms $\Psi_{16}$ and $\Psi_{14}$ are shown extended over the 0$^\circ$ to 60$^\circ$ forward sector.

Figure 3: The cross correlation ratios $C_{16|14}(16, \Theta)$ and $C_{16|14}(14, \Theta)$ optimized for the 10$^\circ$ window centered at 10$^\circ$ azimuth, 0$^\circ$ elevation. (See arrow).
In Fig. 2, we plot the calculated cross correlation amplitudes for the two best chaos based waveforms $\Phi_{A|B}^{max}$ and $\Phi_{A|B}^{min}$ optimized to distinguish target 16 from target 14 in the angular window $10^\circ \pm 5^\circ$ (arrow). In that region $\langle |R(\Phi_{max}^{16}|14(\Theta)) \rangle > \langle |R(\Phi_{max}^{14}|16(\Theta)) \rangle$ and $\langle |R(\Phi_{min}^{16}|14(\Theta)) \rangle < \langle |R(\Phi_{min}^{14}|16(\Theta)) \rangle$.

Taking the ratios of the cross correlations in Fig. 2 we find the contrasts shown in Fig. 3.

In Fig. 4, we plot the ten degree window contrast differences, $D_{16|14}^{|14}(\Theta)$, for $5^\circ$ angular increments between $0^\circ$ and $60^\circ$ in the forward sector. Since the models are symmetric these results apply over the range $-60$ to $+60$. In each case the optimization is driven by the least compatible returned waveform in the window. If the returned waveforms vary rapidly within a window the optimization becomes more difficult. The contrast difference can be increased by narrowing the window and thus reducing the received waveform variation. This can be seen in Fig. 5. In general, narrowing the optimization window increases the contrast difference between targets but may limit the applicability of the method in real situations with angle of approach uncertainty.

4. CONCLUSIONS

We demonstrate that one can distinguish between two similar radar targets using a method based on the optimization of chaos based test waveforms. Two methods were used to construct the test waveforms, concatenation of sinusoids and band pass filtering of the chaotic time series. Both methods resulted in similar optimizations. The optimization process included a Monte Carlo selection of test waveforms with later simplex optimization. The simplex amoeba optimization routine employed was prone to divergences since tweaking the chaotic map parameters can lead to sudden departures from the starting test waveform. Work is proceeding in incorporating more stable optimization routines in the code. We also will be studying the effect of additive noise on the calculated contrasts and the overall discrimination between targets. Angular window size and choice of bandwidth and center frequency and target dimension trade off with contrast difference target discrimination through the rapidity of variation of the waveform pattern with angle of approach.

REFERENCES