Switch Antenna Arrays with Single Receiving Channel for FMCW Radar

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1.Introduction

Linear frequency modulated continuous wave (LFMCW) radar has broad applications in short-range, non-contact target detection and imaging, because of its many advantages such as low transmitting power, small volume, high range-resolution and low cost. Recently, to extract characteristics of images, high angle-resolution is required, which is generally realized by multi-channel antenna array (Fig.1).[1,2] But this scheme is faced with the following problems. First, each sensor needs an individual device, which results in high cost. Second, to achieve higher angle-resolution, antenna aperture has to be increased, which expands device volume. Third, the difference of gain and phase between channels will deteriorate resolution accuracy. In this paper, a new time-division switch antenna array (Fig.2) is proposed to overcome the above three problems, in which only one set of transmit/receive device is required (hence each channel has the same property) and the antenna aperture is reduced to half of multi-channel antennas.

2.Principle and performance analysis

Assume that FMCW systems' source has a saw-waveform frequency-time relation. The frequency modulation period is T, and the sweeping bandwidth is B. There are M sensors in the array, which work in turn. In each period, only one sensor works, while the others are turned off.

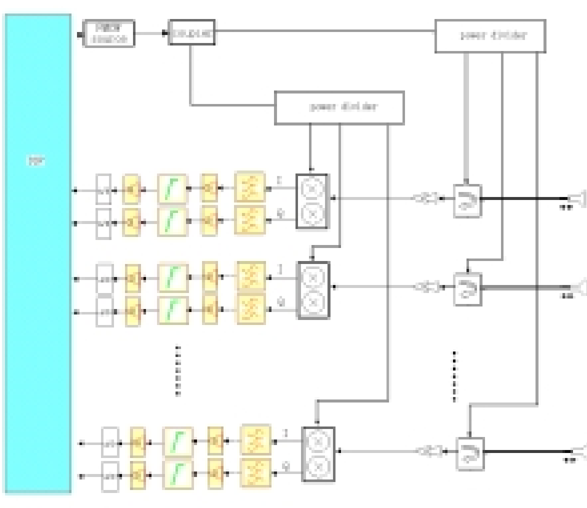

Fig1. Multi-channel antenna array system.

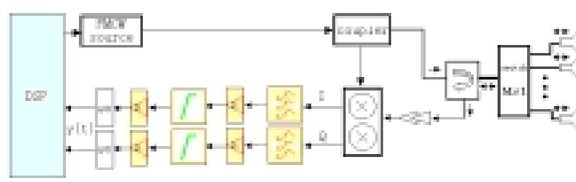

Fig.2 Switch antenna array system.

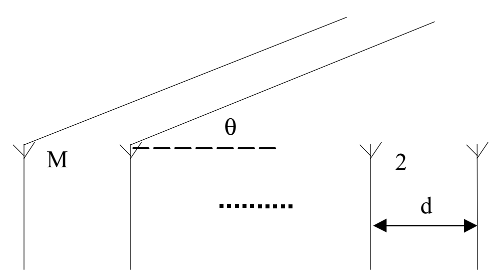

Fig.3 Schematic antenna array.

Suppose L is number of targets with their radial velocity υ_i , angle θ_i and distance r_i , the signal output of the frequency-modulated source is: $S_t(t) = A_t \cos[2\pi\ (f_0 t + \frac{1}{2} k\ t^2) + \phi_0] \quad 0 < t < T$

The system work process comprises two cycles. In the first cycle, sensors work in turn from the 1st to the

Mth. The back scattered signal received by the kth sensor is:

$$S_k(t)=\sum_{i=1}^{L} a_i \cos\left\{\ 2\pi[f_0(t-\tau_i)+\frac{1}{2}k(t-\tau_i)^2-\frac{2d\sin\theta_i+v_i T}{\lambda}(k-1)]+\phi_0\ \right\}$$

where $\tau_i=\frac{2r_i+\upsilon_i t}{c}$. (1)

After mixer and I/Q detection, it becomes:

$$y_k(t)=\sum_{i=1}^{L} x_i(t)\exp\left\{-j(\frac{2\pi(2d\sin\theta_i+v_i T)}{\lambda}(k-1))\right\}+n_k(t)$$

where $x_i(t)=a_i\cos\{j(2\pi f_i t+\varphi_i)\}+n(t)$ $f_i=\frac{2kr_i}{c}+\frac{2\upsilon_i}{\lambda}$ $\varphi_i=2\pi[f_0\tau_i-\frac{1}{2}k\tau_i^{\ 2})]$ (2),and $n_k(t)$ is noise. f_i can be estimated from any $y_{rk}(t)$. Then MTD processing (Moving Target Detection) is done and r_i and υ_i can be obtained.

Arrange $y_k(t)$ for all sensors to a vector:

$Y_1(t)=A(\overline{\xi}_1)X(t)+N(t)$ (3)

where subscript "1" indicates the first cycle, and

$x_i(t)=a_i\exp\{\ j(2\pi\ f_i t)+\phi_i\}$ $X(t)=[x_1(t)\quad x_2(t)\quad\cdots\quad x_L(t)]^T$ $N(t)=[n_1(t)\quad n_2(t)\quad\cdots\quad n_M(t)]^T$

$A(\overline{\xi}_1)=[a(\xi_{11})\quad a(\xi_{12})\quad\cdots\quad a(\xi_{1L})]^T$ $\overline{\xi}_1=[\xi_{11}\quad\xi_{12}\quad\cdots\quad\xi_{1L}]^T$

$a(\xi_{1i})=[1\quad\exp(\xi_{1i})\quad\cdots\quad\exp(\xi_{1i}(M-1))]$ $\xi_{1i}=\frac{2\pi(2d\sin\theta_i+v_i T)}{\lambda}$ (4)

Because noise and signals (all frequencies) are non-correlated each other, the auto-correlation matrix of $Y_1(t)$ can be derived as: $R_{Y1}=E\{Y_1Y_1^H\}=A(\overline{\xi}_1)\Lambda A^H(\overline{\xi}_1)+\sigma_\omega I$ (5-a)

Meanwhile, we have $\hat{R}_{Y1}=\frac{1}{N}\sum_{l=1}^{N}Y_1(t_l)Y_1^H(t_l)$ (5-b)

where N is snapshots. From (5-a) and (5-b), we can get $\overline{\xi}_1$ by beam-former or MUSIC etc.

In the second cycle, sensors work in a reverse order, i.e. from the Mth to the 1st. Similarly, we have:

$R_{Y2}=E\{Y_2Y_2^H\}=A(\overline{\xi}_2)\Lambda A^H(\overline{\xi}_2)+\sigma_\omega I$ (6) $\xi_{2i}=\frac{2\pi(-2d\sin\theta_i+v_i T)}{\lambda}$ (7)

From (6), we can get $\overline{\xi}_2$, Combining (4) and (7), we have equation: $\xi_{1i}-\xi_{2i}=\frac{2\pi(4d\sin\theta_i)}{\lambda}$ (8)

Then, the bearing of the ith target θ_i is calculated.

Now let's see the resolution performance of this method. Assume the object is in ($-\theta_m$, θ_m), α is the super-resolution weighting factor, which is dependent on algorithms, sensor number and target distribution. Generally, for FFT $\alpha=1$, and for MUSIC, $\alpha=1/3-1/5$. In switch antenna array, $\Delta\xi_{1i}=\Delta\xi_{2i}=\frac{2\pi\alpha}{M}$, hence

$\Delta(\xi_{1i}-\xi_{2i})=\frac{4\pi\alpha}{M}$ (9). From (8), we have $\Delta(\xi_{1i}-\xi_{2i})=\frac{8\pi d\sin\Delta\theta_i}{\lambda}$ (10).

(9) and (10) indicates: $\sin\Delta\theta_i=\frac{\alpha\lambda}{2Md}$ (11)

In the multi-channel array, $Y(t) = GA(\bar{\xi})X(t) + N(t)$ where $\bar{\xi}_i = \frac{2\pi d \sin\theta_i}{\lambda}$ $\Delta\bar{\xi}_i = \frac{2\pi\alpha'}{M}$ $(\alpha' \geq \alpha)$ G indicates the complex response of individual channel. Similarly, we have $\sin\Delta\theta'_i = \frac{\alpha'\lambda}{Md}$ (12)

Comparing (11) and (12), we can derive: $\sin\Delta\theta'_i \geq 2\sin\Delta\theta'_i$, hence $\Delta\theta'_i \geq 2\Delta\theta'_i$.

It is clearly seen that for the same antenna aperture, the resolution of switch antenna array is two times that of traditional multi-channel antenna array. In other words, for same resolution, the aperture of one-dimension switch antenna is reduced to 1/2, while in two-dimension case reduced to 1/4.

A more comprehensive comparison between the two kinds of arrays is shown in the following table.

	Number of devices	Angle-resolution	Computation complexity	Processing time	Required processor speed
Switch antenna	1 set	$\leq \frac{\Delta\theta}{2}$	2A	2MT	L/M
Multi-channel antenna	M set	$\Delta\theta$	A	T	L

If vT satisfies $v_{MAX} < \frac{2d\delta\theta}{T}$ (13), where $\delta\theta$ is required accuracy, its influence on θ is negligible, then only the first work cycle is needed. (13) is not a strict restriction, which is fulfilled in many applications such as domestic monitor, industrial supervision. Still another case is that the influence of vT is so considerable that appropriate corresponding relationship between the two cycles cannot be set up and wrong estimation may happen. This problem will be discussed in another paper where a novel signal processing method is proposed to deal with it.

3.Simulation results

The system work frequency band is 10GHz, sweeping bandwidth B=500MHz, antenna work period T=0.05ms (20kHz). M=8 is the number of sensors.

The two target to be estimated have their velocities, distances, and angle υ_1=25km/h, υ_2=15km/h, r_1=15m, r_2=50m, θ_1=1 θ_2=-4 respectively. The relative signal amplitude of the two targets are 1 and 3, and the number of snapshots is 512. In searching process, the angle step is 0.05 degree.

Fig. 3 is the resolution results of multi-channel antenna array with sensor spacing $d = \frac{\lambda}{3}$. It is seen that the two targets are blended and only one target is detected at θ_1=-3.8° .Fig. 4 is the resolution result of switch antenna array under the same condition. The first subfigure shows the estimated $\bar{\xi}_1$ from the first cycle. For clarity, ξ_{11} and ξ_{12} have been transformed to angle in degree by multiplying a factor $\eta = \frac{4\pi d}{\lambda} \times \frac{\pi}{180}$=13.66 The two angles shown are $\eta \times \xi_{11}$=-4.5° and $\eta \times \xi_{12}$=0.25° . The second subfigure shows the estimated - $\bar{\xi}_2$ from the second cycle. Similarly, the two angles shown are $-\eta \times \xi_{21}$=-3.3° and $-\eta \times \xi_{22}$=2.05° . In the third subfigure, the results from the two cycles are placed together, and processed to produce the final results. Since $\theta = \arcsin(\frac{\lambda}{4\pi d}\bar{\xi}) \times \frac{180}{\pi} \approx \eta \times \bar{\xi}$, we have $\theta_1 = \eta \times \frac{\xi_{11} - \xi_{12}}{2}$=-3.9° $\theta_2 = \eta \times \frac{\xi_{21} - \xi_{22}}{2}$=1.15° It can be seen that the resolution result is rather.

Doubling the sensor spacing to $d = \frac{2\lambda}{3}$, we can see that multi-channel antenna array also detects the two targets. (See Fig.5) The result is θ_1=-3.9°, θ_2=1.3°. It is seen that the resolution accuracy is even a little lower than switch antenna with sensor spacing $d = \frac{\lambda}{3}$.

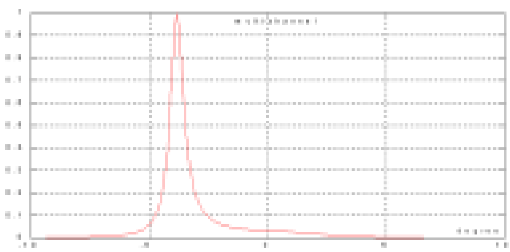

Fig.3 Resolution result of two targets at –4° and 1° by multi-channel antenna array with sensor spacing $d = \frac{\lambda}{3}$.

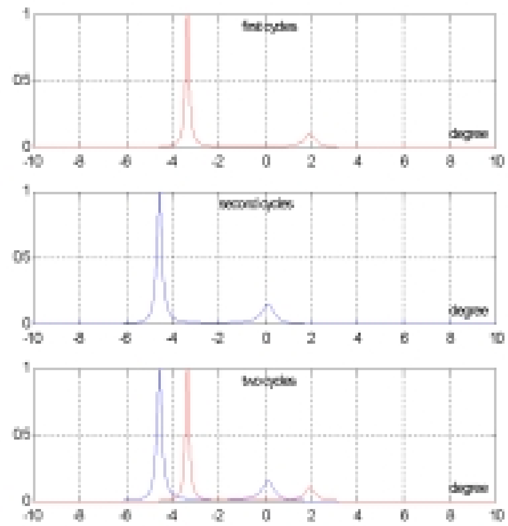

Fig.4 Resolution result of two targets at –4° and 1° by switch antenna with sensor spacing $d = \frac{\lambda}{3}$.

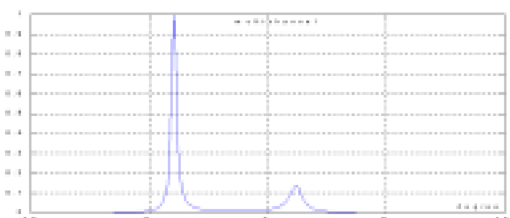

Fig.5 Resolution result of two targets at –4° and 1° by multi-channel antenna with spacing $d = \frac{2\lambda}{3}$.

IV Conclusion

We propose a new switch antenna array to substitute traditional multi-channel antenna array. Both principle analysis and simulation results have demonstrated that, it can achieve same or better resolution result while only using half-sized antenna aperture and one set of device. It can be deduced that, in two-dimension antenna array, the antenna aperture can be 1/4 that of multi-channel antenna array, if same resolution accuracy is required. Expectedly, this switch antenna array will reduce the FMCW system volume and cost, and satisfy the more and more demanding application requirements.

Reference

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