COHERENT MIMO RADAR FOR GMTI

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1. INTRODUCTION

The use of the MIMO (Multiple-Input Multiple-Output) principle for radars is an emerging research field. Two kinds of MIMO radar systems can be distinguished which are either based on coherent or non-coherent operation. The case of coherent MIMO radars will be considered in this paper. Coherent MIMO radars have a high potential in remote sensing for various applications such as imaging [1, 2, 3, 4] and target detection [5, 6, 7].

In this paper, we consider MIMO systems with optimized element distributions as presented in [8], i. e. the N_{TX} TX elements are located at the edges of the array and the N_{RX} RX elements are arranged in between. Through adapted antenna excitation, a fully filled antenna array of $N_{virt} = N_{TX} \times N_{RX}$ virtual antenna elements is synthesized. The MIMO operation leads to a much lower number of $N_{TX}+N_{RX}$ real antenna elements in comparison to the corresponding phased antenna array of N_{virt} elements. The number of antenna elements can be further decreased while the length of the array is kept constant, which causes the occurrence of grating lobes. The equivalent baseline between the outer virtual elements of the MIMO configuration is almost twice as large as the one of the corresponding phased-array system. This allows detection of slower moving targets as the MDV (Minimum Detectable Velocity) is reduced and also leads to better estimation of the target parameters. MIMO configurations have therefore a large potential for GMTI (Ground Moving Target Indication). However, the SNR (Signal-to-Noise Ratio) of MIMO systems is lower compared to phased-array systems, as the TX antennas of MIMO systems transmit "incoherently" while they transmit "coherently" for phased-array systems. This is because the signal of each SISO (Single-Input Single-Output) channel has to be individually retrieved for MIMO radars. There are basically two alternatives to separate the different transmitted signals for each receive channel. One possibility is to activate the TX antennas one after the other for each pulse in a cyclic way. However, such a scheme gives away SNR and reduces the effective PRF (Pulse Repetition Frequency) by the number of TX elements, which may cause signal sub-sampling depending on the array geometry. To improve both SNR and effective PRF, all TX antennas have to transmit orthogonal signals at the same time.

The scope of this paper is to derive a signal model for GMTI and to analyze different MIMO configurations based on spatial, frequency, and waveform diversity for their GMTI performance.

2. SIGNAL MODEL AND SIGNAL PROCESSING FOR GMTI

2.1. Geometry

Let's consider an antenna array with the TX elements located at positions $\mathbf{x}_n^{TX}(T) = (\Delta x_n^{TX} + v_a T, y_n^{TX}, h)^\dagger$ with $n = 1, \ldots, N_{TX}$ and the RX elements at positions $\mathbf{x}_m^{RX}(T) = (\Delta x_m^{RX} + v_a T, y_m^{RX}, h)^\dagger$ with $m = 1, \ldots, N_{RX}$ at time T. The antenna array moves in x-direction with the velocity v_a at the altitude h. The mean range between a point scatterer P with coordinates $\mathbf{x}_p(T) = (x_{p_0} + v_{p_x} T, y_{p_0} + v_{p_y} T, 0)^\dagger$ and the n-th TX and m-th RX antenna pair is given at time T by

$$R_{nm}(\mathbf{x}_p, T) = \frac{|\mathbf{x}_p(T) - \mathbf{x}_n^{TX}(T)| + |\mathbf{x}_p(T) - \mathbf{x}_m^{RX}(T)|}{2} \simeq |\mathbf{x}_p(T) - \mathbf{x}_i(T)| \qquad (1)$$

with $\mathbf{x}_i$ the position of the i-th virtual antenna located at the center of gravity of the position of the considered TX and RX antenna pair. This equation is only valid when P is situated in the far field of the antenna array. The motion of the point scatterer P is described by its along-track velocity v_{p_x} and its across-track velocity v_{p_y}. The range can be approximated after Taylor expansion by

$$R_{nm}(\mathbf{x}_p, T) \quad \simeq \quad R(\mathbf{x}_p, T) - \Delta x_i u(\mathbf{x}_p, T) - \Delta y_i v(\mathbf{x}_p, T) \qquad (2)$$

with the range to the center of the array $R(\mathbf{x}_p, T) = \sqrt{(x_{p_0} + (v_{p_x} - v_a)T)^2 + (y_{p_0} + v_{p_y} T)^2 + h^2}$ and the unity LOS (Line Of Sight) vector $\mathbf{u}(\mathbf{x}_p, T) = (u(\mathbf{x}_p, T), v(\mathbf{x}_p, T), w(\mathbf{x}_p, T))^\dagger$ defined by $u(\mathbf{x}_p, T) = \frac{x_{p_0} + (v_{p_x} - v_a)T}{R(\mathbf{x}_p, T)}$ and $v(\mathbf{x}_p, T) =$

$\frac{y_{p_0}+v_{p_y}T}{R(\mathbf{x}_p,T)}$. The corresponding radial velocity common to all virtual antennas (far field condition) is expressed by

$$v_r(\mathbf{x}_p,T) \quad \simeq \quad (v_{p_x}-v_a)u(\mathbf{x}_p,T)+v_{p_y}v(\mathbf{x}_p,T) \tag{3}$$

leading to the Doppler frequency $f_d(\mathbf{x}_p,T) = -\frac{2}{\lambda_0}v_r(\mathbf{x}_p,T)$ with λ_0 the radar wavelength.

In this paper, we consider a Post-Doppler STAP (Space-Time Adaptive Processing) approach for target detection in order to compare the different MIMO concepts. Other processing methods can be used leading to similar comparison results e. g. ISTAP (Imaging STAP) [9], where an integration over the target history is performed to increase the target SNR and hence the target detection performance. For that, we consider a CPI (Coherent Processing Interval) around the time T_0 during which a target stays in a range-Doppler cell, i. e. the radial velocity and the LOS of the target can be assumed to be constant over that CPI. The range to the target can be approximated over this time interval by

$$R_{nm}(\mathbf{x}_p,T) \quad \simeq \quad R(\mathbf{x}_p,T_0)+(T-T_0)v_r(\mathbf{x}_p,T_0)-\Delta x_i u(\mathbf{x}_p,T_0)-\Delta y_i v(\mathbf{x}_p,T_0). \tag{4}$$

In the following, we denote by R the range between the array center to the target, v_r the target radial velocity, and $\mathbf{u}=(u,v,w)^\dagger$ its LOS vector to simplify the mathematical expressions.

2.2. Signal model

The signal $\mathbf{Z}$ received by the whole MIMO system in the range-Doppler cell (R, f_d) can be written as the superposition of the target signal $\mathbf{S}$ with parameter vector $\boldsymbol{\vartheta}=(v_r,\mathbf{u})^\dagger$ including radial velocity and LOS vector, the clutter signal $\mathbf{C}$ and the noise signal $\mathbf{N}$

$$\mathbf{Z} = \mathbf{S}(\boldsymbol{\vartheta})+\mathbf{C}+\mathbf{N}. \tag{5}$$

The clutter can be cancelled using the information redundancy between the SISO channels. In the following, the moving target signal and the theoretical clutter-plus-noise covariance matrix are derived for different types of MIMO configurations.

2.3. Spatial diversity

This scheme is analog to the Time Division Multiple Access (TDMA) in the communications field. In order to avoid any coherent superposition of the TX signals, which would result in the non-separation of the different SISO signals, the TX antennas are activated individually from pulse to pulse in a cyclic way. Consequently, the cross-correlation between the signals of two RX antennas acquired at different pulses is null. The sidelobes of the auto-correlation function of each TX signal in the range-Doppler domain can be reduced by using a window function. The switching period is given by $\frac{N_{TX}}{PRF}$ and the effective PRF by $PRF_{eff}=\frac{PRF}{N_{TX}}$.

The spatial diversity strategy is a generalization of the antenna aperture switching approach presented in [10] and experimentally demonstrated in [11]. The order of the antenna switching plays a role in the GMTI performance. Better performances are reached for switching orders close to the DPCA (Displaced Phase Center Antenna) condition.

2.3.1. Target signal

According to [10], the moving target signal in the range-Doppler cell (R, f_d) can be expressed after pre-processing including range compression, multiplication by a 2D window function, and transformation in the Doppler domain by

$$\mathbf{S}(\boldsymbol{\vartheta}) = \alpha e^{-j\frac{4\pi}{\lambda_0}R}D^2(\mathbf{u})\mathbf{T}_S\big(\mathbf{d}_{\text{space}}(\mathbf{u})\otimes\mathbf{d}_{\text{time}}(v_r)\big) \tag{6}$$

with $\otimes$ the Kronecker product and λ_0 the radar wavelength. α is the target reflectivity. The two-way antenna characteristics which is assumed to be constant for all the antenna pairs is denoted by D. The spatial DOA (Direction of Arrival Vector) vector is given by

$$\mathbf{d}_{\text{space}}(\mathbf{u}) = \left(e^{j\frac{4\pi}{\lambda_0}(\Delta x_i u+\Delta y_i v)}\right)_{i=1,\dots,I_{virt}} = \mathbf{d}_{\text{TX}}(\mathbf{u})\otimes\mathbf{d}_{\text{RX}}(\mathbf{u}) \tag{7}$$

with $\mathbf{d}_{\text{TX}}(\mathbf{u}) = \left(e^{j\frac{2\pi}{\lambda_0}(\Delta x_n^{TX}u+\Delta y_n^{TX}v)}\right)_{n=1,\dots,N_{TX}}$ and $\mathbf{d}_{\text{RX}}(\mathbf{u}) = \left(e^{j\frac{2\pi}{\lambda_0}(\Delta x_m^{RX}u+\Delta y_m^{RX}v)}\right)_{m=1,\dots,N_{RX}}$. The temporal vector takes into account the time delay between the different SISO channels

$$\mathbf{d}_{\text{time}}(v_r) = \left(e^{-j\frac{4\pi}{\lambda_0}v_r\frac{l-1}{PRF}}\right)_{l=1,\dots,N_{TX}}. \tag{8}$$

The transformation matrix $\mathbf{T}_S$ with dimension $N_{TX}N_{RX}\times N_{TX}^2N_{RX}$ describes the switching order.

2.3.2. *Clutter-plus-noise covariance matrix*

This section will be completed in the full paper.

2.4. Waveform diversity

In comparison to the spatial diversity strategy, the SNR and the effective PRF can be improved by a factor of N_{TX} using the waveform diversity approach i. e. all TX antennas transmit simultaneously orthogonal waveforms occupying the same frequency band. The waveform diversity scheme corresponds to the Code Division Multiple Access (CDMA) in the communications field. Each RX channel receives the N_{TX} codes and the separation of the TX contributions is performed by code matching during signal processing. A large number of orthogonal waveforms were already designed for different radar applications e. g. [3, 12]. For GMTI, Doppler tolerant codes should be used. A suitable window function can help to lower the sidelobes of the auto-correlation functions in the range-Doppler domain. However, the cross-correlation between the waveforms never completely disappears even for orthogonal codes. The level of the cross-correlation functions has a strong influence on the GMTI performance as it increases the rank of the covariance matrix. It should be minimized to decrease the mutual interferences.

2.4.1. *Target signal*

In the case of waveform diversity, the moving target signal in the range-Doppler cell (R, f_d) can be expressed after preprocessing (including range compression with matched filter bank, multiplication by a 2D window function to reduce the sidelobe levels, and transformation in the Doppler domain) by

$$\mathbf{S}(\boldsymbol{\vartheta}) = \alpha e^{-j\frac{4\pi}{\lambda_0}R} D^2(\mathbf{u})\big(\mathbf{d}_{\text{space}}(\mathbf{u}) + \Delta\mathbf{d}_{\text{waveform}}\big) \tag{9}$$

where the waveform vector takes into account the cross-correlation between the different waveforms

$$\mathbf{d}_{\text{waveform}} = \sum_{l=1}^{N_{RX}-1} \text{circ}(\mathbf{d}_{\text{TX}}(\mathbf{u}), l) \otimes \mathbf{d}_{\text{RX}}(\mathbf{u}) \tag{10}$$

with circ the circular shift operator. Δ denotes the maximum value of the cross-correlation function normalized by the one of the auto-correlation function. We assume here that all the waveforms have similar auto-correlation functions and cross-correlation functions. In this case, there is no need to rotate the transmitted waveform from pulse to pulse for each TX channel to improve diversity (symmetry property).

2.4.2. *Clutter-plus-noise covariance matrix*

This section will be completed in the full paper.

2.5. Frequency diversity

This section will be completed in the full paper.

3. GMTI PERFORMANCE ANALYSIS

The chosen GMTI metrics to analyze GMTI performance are the SCNR (Signal-to-Clutter-plus-Noise Ratio) and the CRB (Cramér-Rao Bound) for the estimation of the target position as presented in [4].

The system MIRA-CLE X [13] mounted on a platform moving at a velocity of 50 m/s is taken as an example to investigate and compare the GMTI performance of the different MIMO configurations. This MIMO radar operates in X-band and is realized by a linear antenna array consisting of 16 TX elements and 14 RX elements arranged in the ARTINO configuration. We assume a SNR and a CNR of both 15 dB per SISO channel after pre-processing.

3.1. Antenna array in along-track (Side-looking configuration)

In the full paper, the GMTI performance of MIRA-CLE X oriented in along-track in a side-looking configuration will be investigated. This array configuration is particularly adapted to reduce the azimuth ambiguities due to sub-sampling in azimuth for SAR imaging. It relaxes the condition put on the minimum PRF as the waves are sampled at different azimuth positions (spatial sampling) in addition to the temporal azimuth sampling.

3.2. Antenna array in across-track (Forward-looking configuration)

In the full paper, the GMTI performance of MIRA-CLE X oriented in across-track in a forward-looking configuration will be investigated. This antenna orientation corresponds to the one of the ARTINO system [1] and enables a 3D imaging of the scene. Contrary to the along-track arrangement, the across-track configuration does not relax the minimum PRF.

4. CONCLUSION

MIMO radars are much cheaper and lighter than radar systems with phased-array antennas because a much lower number of antenna elements is needed. Moreover, the equivalent array length of MIMO systems is about twice as large as the one of their corresponding phased array systems making them particularly sensitive for moving target detection if the array is oriented in along-track. Because their SNR is lower than the one of phased array systems, MIMO radars are particularly adapted for low-cost short range applications. That makes them very attractive for small UAVs requiring a light payload with low energy consumption.

5. REFERENCES

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