Advanced Methodologies of Active and Passive Ground-Based Imaging Radar for Environmental Monitoring

Ph.D. Dissertation

Advanced Methodologies of Active and Passive Ground-Based Imaging Radar for Environmental Monitoring

（環境計測のための能動および受動地上設置型イメージングレーダの研究）

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Abstract

Imaging radar is an important remote sensing technique that has been used for a broad range of applications. For imaging radar, spatial and temporal resolutions are two critical characteristics that determine its applicability and performance in practice. By using a wide frequency bandwidth and exploiting the relative movement between the radar platform and the observation scene, synthetic aperture radar (SAR) can achieve high spatial resolutions in the range and azimuth directions without using lots of antenna elements. By using the differential interferometric SAR technique, object movement and displacement along the time direction can also be measured. As an effective complement to space-borne SAR and airborne SAR, ground-based SAR (GB-SAR) has been extensively applied for contactless, real-time, continuous, high-resolution, and high-accuracy imaging and displacement estimation purposes. Although has been rapidly developed to a mature technique and has been successfully employed for various applications during the last two decades, the performance of GB-SAR should be and can be further improved, which is the main motivation of this work. This thesis intends to contribute to the data acquisition period reduction, imaging quality improvement, and system flexibility increasing for GB-SAR.

A dimension-reduced compressive sensing (CS) based method with the multiple measurement vector (MMV) model has been proposed for GB-SAR imaging. Based on the sparse assumption of the imaging scene, which can be satisfied in most GB-SAR applications, much fewer samplings than that suggested by Nyquist theory have been used to reduce the data acquisition time of GB-SAR. To reduce the computing complexity, the supporting region of significant objects in the observation scene has been extracted for the following sparse reconstruction step. To improve the coherence of different SAR images and the displacement estimation accuracy, the MMV model has been used to exploit the relationship of multiple measurements. Compared to the conventional matched filtering based GB-SAR imaging methods, the proposed method can achieve accurate and sidelobe-reduced displacement estimation results with the under-sampled data. Compared to the existing CS based GB-SAR imaging method, the accuracy of displacement estimation and the calculation speed can be improved. Two field experiments have been carried out to assess the performance of the proposed method in practice.

To increase the data sampling rate of GB-SAR in the data acquisition stage, two linear MIMO radar systems and one cross MIMO radar system have been fabricated for high-resolution 2D and 3D SAR imaging and high-accuracy displacement estimation purposes. At first, based on phase center approximation (PCA), the MIMO array design methods have been studied. The equivalence between the linear MIMO array and the virtual uniform linear array (ULA) and the equivalence between the cross MIMO array and the virtual uniform planar array (UPA) have been analyzed. Then, conventional GB-SAR imaging algorithms have been modified to MIMO radar applications. To suppress the high-level imaging artifacts (sidelobes and grating lobes) caused by the system errors, several filtering based approaches, i.e., Wiener post-filter, coherence factor (CF), and phase CF (PCF), have been employed and modified. Various experiments with different objects, such as trihedral corner reflections (CR), bridge, buildings, and trees, have been carried out to validate the developed MIMO radar systems and the proposed processing methods.

In order to improve the performance of the developed linear MIMO radar system for short-range target imaging with system errors, a novel processing model for CS based imaging method, which takes the azimuth-dependency of target complex amplitude into consideration, has been proposed. Based on the block sparse property of the received signal in the defined measurement matrix, 2D SAR images of the targets can be obtained at each spatial sampling point by the modified block orthonormal matching pursuit (BOMP) algorithm. Then, a cross-correlation based method has been employed to fuse these 2D SAR images to obtain the final result. Random under-samplings of frequencies and spatial sampling points have been conducted to reduce the data acquisition time, memory usage, and computational complexity. Experiment results show that, compared with the conventional matched filtering based imaging methods, the proposed method can provide artifacts-reduced higher-resolution SAR images with reduced samplings. In comparison with the classical CS based imaging methods, due to the more suitable established observation model, the proposed method can achieve better imaging results with fewer artifacts.

A 3D pseudopolar coordinate has been established, based on which the first-ordered far-field pseudo-polar image format algorithm (FPFA) has been extended to its 3D version for effective and high-resolution 3D SAR imaging of the designed cross MIMO radar system. A spatially variant apodization (SVA) based method has been applied to adaptively suppress the strong sidelobes in the range, azimuth, and elevation directions. Considering the sparsity of the observation scene, the tensor CS (T-CS) based imaging method has been used to reduce the data sampling time, which has been implemented in the data acquisition stage by randomly select several transmitter and receiver pairs. Then, in order to solve the T-CS problem efficiently and accurately without fine-tuning the input parameters, a tensor-based iterative adaptive approach (T-IAA) has been proposed. Experiments with two trihedral CRs as the point targets and a four-floor building as the distributed target have been conducted to evaluate the proposed imaging methods. It has been found that the proposed methods can achieve better performance than conventional methods and the computing complexity can also be reduced.

The practical applications of the developed MIMO radar systems and the proposed imaging

methods have been conducted for target 2D displacement vector estimation and tunnel movement monitoring. By using two linear MIMO arrays with a specified spatial baseline, the displacement components in two line of sight (LoS) directions have been measured. According to the relative geometry and the least squares (LS) based method, the 2D displacement vector of the target in the Cartesian coordinate has been derived. The determination method of the spatial baseline between two MIMO arrays has been proposed based on the displacement estimation precision analysis. Together with a commercial frequency-modulated-continuous-wave (FMCW) based MIMO radar system, the tunnel movement during construction and before reconstruction have been monitored by the designed cross-MIMO radar system. To improve the angular resolution of the FMCW based MIMO radar system, super-resolution algorithms and the Kronecker CS based method have been applied. The tunnel experiment results with a short interval of 72 s and a long interval of 16.5 hours have shown that the MIMO radar based technique can indeed estimate the tunnel movement with sub-millimeter accuracy.

Passive bistatic radar (PBR) has been researched in order to improve the system flexibility and reduce the cost of GB-SAR and MIMO radar. In the first fundamental study stage, characteristics of digital TV signal and WiFi signal, such as their working frequency, bandwidth, transmitting power, and ambiguity functions, have been assessed. Software-defined radio (SDR) based data sampling has been introduced. Signal models of PBR for moving target range-Doppler mapping and stationary target high-resolution SAR imaging have been established, based on which the signal processing procedures for PBR have been briefly reviewed. Then, for the digital TV signal which employs the Integrated Services Digital Broadcasting-Terrestrial (ISDB-T) as its standard, a template reference signal reconstruction and modification method has been proposed. With the reconstructed reference signal, the influences of multipath signal and noise can be much reduced. By modifying the pilot carriers, the sidelobes of the ISDB-T digital TV signal in the range-Doppler domain can be effectively suppressed.

For PBR moving target detection, by exploiting the sparsity of the scene containing only a few moving targets, a high-resolution and real-time range-Doppler map generation algorithm has been proposed. In the proposed algorithm, the long integration time has been divided into multiple short batches, from which a few batches have been randomly selected on the basis of CS theory. Cross-correlation has been performed for each selected batch to get the range-compressed profiles. Then, mean-value subtraction has been performed to suppress the direct path interference and stationary target reflections. Finally, an extended orthogonal matching pursuit (EOMP) algorithm has been proposed for the effective estimation of the target Doppler frequency. Practical application of this novel algorithm has been examined by the detection experiment of a landing airplane and multiple

moving ships via two synchronized general-purpose software-defined radio (SDR) receivers. The results have shown that the proposed algorithm can achieve an improved resolution and a reduced sidelobe level compared to the classical batch algorithm.

For PBR stationary target SAR imaging applications, an effective direct path interference (DPI) suppression method has been proposed. Conventional time-domain processing methods cannot mitigate the DPI component in the surveillance channel completely and will introduce some errors into the target position estimation. By exploiting the sparsity of the DPI signal and the properties of its covariance matrix, the proposed method has solved these problems by accurately estimating the delay of DPI based on atomic minimization algorithm and Vandermonde decomposition in the frequency domain. Then, the amplitude of the DPI has been calculated according to the LS based method. Simulation and experiment results of Wireless Fidelity (WiFi) based passive bistatic SAR (PB-SAR) short-range target imaging have validated the performance and advantages of the proposed method in practice. It has been shown that the proposed method can suppress the DPI more effectively and estimate the position of target more accurately than the conventional method.

At last, based on the previous studies of GB-SAR, MIMO radar, and PBR, a passive bistatic GB-SAR (PB-GB-SAR) system without a dedicated transmitter has been developed by using commercial-off-the-shelf (COTS) hardware components for local-area high-resolution imaging and displacement measurement purposes. Different from the FMCW or SFCW signal, which is commonly used by GB-SAR and MIMO radar, the continuous digital TV signal broadcast by a geostationary satellite has been adopted by PB-GB-SAR. To increase the coherence between two receiving channels, a frequency and phase synchronization method has been proposed for the low noise blocks (LNBs). To achieve the well-focused SAR image, back projection algorithm, range migration algorithm, and far-field pseudo-polar image format algorithm, specified for PB-GB-SAR applications, have been formulated. To suppress the strong artifacts caused by the amplitude-filter spectrum and the frequency gaps among different TV channels, super-SVA based method, low-rake matrix completion (MC) based, CS based, and approximated observation CS based methods have been proposed. Field experiments with various targets have been carried out to validate the designed PB-GB-SAR system and the proposed methods. The developed PB-GB-SAR system can image the targets within 100 meters effectively and estimate the displacement with millimeter accuracy. Therefore, PB-GB-SAR can indeed reduce the built and maintenance cost, increase the system flexibility, and obtain different scattering properties of the observation scene, while the continuous illumination, high-resolution imaging, and high-accuracy displacement estimation capacities of GB-SAR have been kept.

Keywords: Radar imaging, synthetic aperture radar (SAR), differential interferometry, ground-based synthetic aperture radar (GB-SAR), MIMO radar, passive bistatic radar (PBR), passive bistatic synthetic aperture radar (PB-SAR), compressive sensing (CS), orthonormal matching pursuit (OMP), low-rake matrix completion (MC).