Study on near range high resolution 3D radar imaging

著者	Lyulyakin Andrey
号	16
学位授与機関	Tohoku University
学位授与番号	学術(環)博第253号
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<tr><td>氏　　　　　　　名</td><td>アンドレイリュリャキン</td></tr>
<tr><td>授　与　学　位</td><td>博士（学術）</td></tr>
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<tr><td>指　導　教　員</td><td>東北大学教授　佐藤　源之</td></tr>
<tr><td>論　文　審　査　委　員</td><td>主査　東北大学教授　佐藤　源之　　東北大学教授　伊藤　高敏
　　　東北大学教授　陳　強　　　　本間　尚樹 教授
　　　　　　　（工学研究科）　　　　（岩手大学）</td></tr>
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論 文 内 容 要 旨

Three-dimensional imaging techniques have been developed for a wide area of applications, including the applications in near field such as ground penetrating radar imaging, hidden object imaging and security control. Different types of active radar systems have been by many research institutions, developing new technologies of imaging every day. This work is motivated by investigation of 3D imaging with two types of continuous wave radars and its specificities, mainly focused on optimization technic of the antenna arrays and tracking of the radar.

In order to get information about objects inner structure, to detect and recognize shapes of the objects a high resolution radar imaging have been used. However, the technology, based on ultra-wideband (UWB), is limited by microwave propagation effects, wave scattering, and power loss. Operating of the radar in the near-field could overpass the problem of the received signals been weak and noisy. Such UWB imaging systems are used for various applications such as imaging through obstacles, security and medical area. Active radar systems have been used for it, covering a large area of operating frequency ranges, from less than 100 MHz up to the 350 GHz, with the frequency range customized for each application.

In these systems, down-range and cross-range resolutions are determined by the frequency bandwidth and size of the antenna arrays. In the classical two-dimensional designs, element spacing is chosen as at most half of the center wavelength to eliminate undesired grating lobes. As a result, in applications demanding high-resolution, classical (non-sparse) planar arrays require high hardware complexity and cost. To reduce this complexity, a sparse array systems have been used due to it.

Depending on the field of application, the spatial sampling can be realized with mechanical scanning techniques or electronic sampling by switching between spatially distributed transmit and receive antennas. Using a synthetic aperture radar (SAR) processing or migration is an essential basis in the near range radar imaging, which can be used in ground penetrating radar (GPR) and ground-based synthetic aperture radar (GB-SAR). In my study I came across several problems on the way to get the high resolution image with Continues Wave (CW) radar. Results of the solving of these problems are introduced in the dissertation.

This research work aims to develop technologies for the near field 3D imaging in different applications. Two types of monitoring systems are discussed. One system is the Step Frequency Continuous Wave Radar (SFCW Radar) with a 2D sparse array antenna used in inspection of the inner wall structure. And second one is the FMCW radar used as a position tracker on the moving objects.

Chapter 2 is dedicated to the problem of optimization of the antenna array. Starting from the benefits of using a sparse array over the dense array, it describes the way of antenna array optimization. In order to improve an imaging performance of a sparse array radar system, an optimization method to find a new antenna array layout was proposed. The method searches the minimum of a cost function based on a 3D point spread function of the array. A few different relations of the L-norm of the reconstructed image were compared. A L0.5-norm maximization for the targets and a L2-norm minimization for the artifacts showed better results compare to others. Relation of these two norms is one of the key features of the method. Another feature is related to making the optimized solution warranted for the different positions of the targets. It is using a random target distribution for an each iteration of the optimization algorithm. Also the accumulating of the cost function, using several combination of the targets at each step of the optimization, was used. It making the optimization process keep away from been stuck in local minimum pushing it to further minimization of the cost function.

The two-dimensional sparse array system has been used for a 3D imaging of the inner structure of building walls, and in order to find the antenna array layout with higher focusing of the targets, the optimization algorithm was applied to this system. The antenna array consists of 32 identical antennas: 16 transmitters and 16 receivers are able to acquire in total 256 channels signal at once. The frequency range of the system is 270MHz to 8GHz. Such wide band allows us to reach a high range resolution. We use spiral patch antennas with circular polarization in order to make the image recognition independent from the target attitude – right-hand circular polarization for transmitting and left-hand for receiving. The antenna consists of two-arm archimedean spirals and a balancing unit to feed them. It has the central frequency around 5 GHz and wide beamlobe with 11, 3 dBi gain. We found a solution for the simulated problem in a form of new layout with sparser middle-point distribution comparing with initial one. The new antenna array was tested at object recognition in laboratory conditions.

In chapter 3 investigate principles of the 3D imaging by mm wave radar. A second system studied in this work is the millimeter wave radar that have been used in 3D imaging due to its specificity of multichannel signal receiving. Different types of migration with this frequency modulated signal radar provide a high resolution imaging of a target, and linear and rotating scanning have been used to achieve it.

3D back projection algorithm was applied to reconstruct an image of a target and succeed in getting a precise position of it. Taking into account that the very high azimuth resolution could be achieved by synthetic aperture radar, the vertical resolution is still could be a problem. 3-channels system however performed quite good results in obtaining the high of the target position, allowed us to propose a way of tracking the radar system using rotating table. The experiment with tracking of the radar was done outside in two dimensions and in three dimensions in laboratory conditions.

Mechanical movement strongly limits this system and keep it away from more advanced applications. Ideally, the millimeter wave radar should be mounted on a free-rotating platform with high movement ability, like a human body. Then a free movement of the system could be used for continues data acquisition, obtaining a high resolution in desirable direction. The problem of such using is the position tracking, requiring for the processing. Indoor tracking system could be using as for beginning.

Chapter 4 united ideas of previous chapters and present a simulations for the antenna arrays for the mm wave radar. The optimization algorithm was applied to the problem of antenna positioning for the MMW radar. The simulation with L0.5L2-norm cost function and random target distribution for 5 and 10 elements linear antenna arrays was done.

The last chapter 5 describing my final thoughts about the work that have been done. Each chapter represent the some ideas that could be developed in the future

（別紙）

論文審査結果の要旨及びその担当者

論文提出者氏名	Andrey LYULYAKIN
論　文　題　目	Study on near range high resolution 3D radar imaging （高精度３次元近距離レーダに関する研究）
論文審査担当者	**主査**　教授　佐藤　源之 教授　伊藤　高敏　　教授　陳　強 教授　本間　尚樹　　（工学研究科） （岩手大学）

論文審査結果の要旨

本論文は近距離イメージング・レーダの最適化とその応用に関するものである。近距離レーダは波長に比べて比較的近い位置にある対象物のイメージングに利用され、環境計測への利用など応用範囲が広い。従来のレーダは波長に比べて極めて遠い場所にある対象物をイメージングするため、対象物はレーダからの見かけ角度の狭い範囲に存在するので位置による距離差が小さいという近似の下でFFTなどの簡易な計算手法を利用することができた。しかし近距離レーダではこの近似が利用できず、イメージングのためのデータ取得量と計算処理量を軽減が学術的な課題となっている。本論文ではこの問題を解決する新たな手法を提案し、電磁界数値シミュレーションと実験で検証している。

本論文は5章から構成されている。第1章は緒論である。

第2章では2次元に配列されたアレイアンテナを利用し、3次元近距離イメージングを行うためのアンテナ配列の最適化について論じている。通常の等間隔アレイアンテナではアンテナ間隔を半波長以下にしないとグレーティングローブによる虚像が発生することが知られている。しかしこの配置では多くのアンテナを密に配列するため装置が大がかりになる。一方送信アンテナと受信アンテナを分離して配置し、多入力、多出力のMIMO構成とすることで虚像の発生を防ぐ手法がスパースアレイ・レーダとして知られている。本章ではスパースアレイ・レーダにおける2次元アレイ配列の最適化手法を提案している。従来の最適化は3次元空間においてレーダ分解能を示す点拡散関数を均等に配置しているが、本論文では点拡散関数をランダムな空間点に対して適用することで、より汎用性の高い最適化が可能であることを見いだしている。またこの結果を実験で検証している。

第３章ではミリ波レーダを利用した3次元高精度イメージング手法について述べている。まずレーダ装置を円弧状に走査して取得したデータに対して合成開口処理による2次元イメージングを行っている。次に走査方向に直交する方向に3つの受信アンテナを配置し、3次元的なイメージングが行えることを示した。この装置を利用し、固定された既知の位置に置かれた反射鏡の相対位置を3次元的に計測することで、レーダ装置の3次元的な位置を計測できることをシミュレーションと実験で示した。例えば本レーダ装置を無人走行車に搭載することで、屋内において走行しながら位置を自動追尾する事が可能となる。

第4章では、第2章で開発したアレイアンテナの最適化を第3章で取り上げたミリ波レーダ装置に適用した場合について、シミュレーションを利用して高精度3次元位置計測、あるいはイメージングに利用する可能性を論じている。

第５章は結論である。

本論文では従来のイメージング・レーダではアンテナを等間隔で1次元あるいは2次元に配置していたが、この制約を外した上でアンテナ配列の最適化を行うことで、効率的なレーダ装置の設計とイメージングが行えることを示した。近距離イメージング・レーダは環境計測、防災減災用のモニタリングなど、今後応用範囲の広がることが期待されている。本論文はこうした技術に新しい知見を与えるものとしての価値が高い。よって、本論文は博士(　学術　)の学位論文として合格と認める。