

博士論文（要約）

Higher-order tensor independent component
analysis: General framework construction
and development of application systems for
MIMO remote sensing of vital signs
（高階テンソル独立成分分析：
汎用枠組みの構築と生体信号のMIMOリモート
センシングのための応用システムの構築）

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Conventional heartbeat and/or respiration sensing systems use contact-type electrodes attached to a human body. However, recent vital-sign detectors sometimes employ noncontact methods. After the first report of detection of respiration using microwaves, there have been a lot of research on respiration and heartbeat measurement based on Doppler radar. Some of them assumed line-of-sight (LOS) situations, while others worked on non-line-of-sight (NLOS) conditions including search and rescue in disasters such as earthquake rubble.

Multiple-input multiple-output (MIMO) configuration using multiple transmitting and receiving antennas holds the ability of target identification intrinsically. For example, a 24 GHz frequency-modulation continuous-wave (FMCW) MIMO radar detects respiration and heartbeat information for respective targets by using target distances to separate the individuals. However, the use of such a high frequency limits its practical applications only within short-range LOS situations. The difficulty is found also in ultrasound sensing systems. A lower-frequency continuous-wave (CW) radar system has the potential to realize target detection with a wider sensitive area even including obstacles.

Environments having obstacles and multiple targets often require separation of a target signal from others and noise. A signal-source separation experiment in an X-band array radar was reported, in which the heartbeat signal of one target was separated from that of another one by using beam-forming successfully. However, a microwave having a lower frequency possesses an advantage though their spatial resolution is a little lower. Microwaves are capable of propagating among obstructions because of their diffractive nature. In such a case, blind source separation (BSS) is expected to enhance the detection and identification ability.

BSS is a framework to estimate individual original signals included in mixed signals based on signal information itself. Independent component analysis (ICA) is a typical method in BSS. ICA eliminates noise and/or separates targets by finding a separation matrix to linearly transform mixed signals into unmixed ones based on signals' statistical property. ICA has been often employed in audio signal processing in the frequency domain.

In the radar sensing and imaging field, an ICA system treated in-phase and the quadrature components obtained by orthogonal detection as two real-number signals different from each other. However, a pair of in-phase and orthogonal components should be processed essentially as a single complex signal. This present thesis also deals with complex signals as an entity. In vital sensing, measurement environment often varies depending on target movement and obstacles. We thus aim to process complex signals adaptively in time-sequential observation. The scheme is called online ICA.

Signal processing in measurement using MIMO configuration leads to a construction of data tensor having multiple axes involving path-category information, rather than a data vector representing mixed signals evenly. A tensor data requires a higher-order tensor for signal separation. Multilinear ICA (MICA) was proposed for applying third-order tensors to ICA processing. MICA uses higher-order singular value decomposition (HOSVD) or higher-order orthogonal iteration (HOOI). Their calculation is based on the tensor decomposition proposed by Tucker. MICA has been positively evaluated for its separation effectiveness.

Though it is true that the methods such as HOSVD and HOOI can process data tensors in the framework of MICA, there is room for utilizing the nature of the higher-order tensors further effectively. In MICA, the categories in the data represented by the tensor axes are nullified by the matricization treatment. It should be possible to realize tensor ICA processing more meaningfully in such a manner that the data categories represented by the axes remain undestructed for enhanced separation performance.

This thesis proposes a novel method of independent component analysis (ICA), which we name higher-order tensor ICA (HOT-ICA). We newly develop a robust microwave multiple input multiple output (MIMO) radar system, in which HOT-ICA performs separation of multiple target signals to detect respiration and heartbeat. In comparison with millimeter waves, microwaves spread wider with diffraction and propagate even in an environment with obstacles to reach targets. However, it often requires more powerful signal separation because of its lower resolution. HOT-ICA realizes high robustness in self-organization of a separation tensor by utilizing channel information, i.e., the information of physical measurement circumstances concerning, e.g., which transmitting/receiving antennas are used. In numerical and living human experiments, our HOT-ICA system effectively separates the bio signals successfully even in an obstacle affecting environment, which has been a difficult task. The results demonstrate the significance of HOT-ICA in remote sensing. It fully utilizes the high dimensionality of the separation tensor by keeping the tensor structure unchanged to take advantage of the measurement circumstances information.

We also propose direction of arrival (DoA) estimation of a target signal based on higher-order tensor independent component analysis (HOT-ICA), a signal processing method that adapts to physical changes in the measurement environment for biological signals. By performing the DoA estimation twice for different antenna sets, we can locate the target at the intersection of the two DoA lines, which is useful in multiple target identification. It also leads to target position estimation by using multiple DoA results. This technology can be used as a system to monitor multiple people simultaneously in places

such as saunas and identify people whose respiration and heartbeat signals are abnormal.

In addition, we propose a method to deal with not only phase but also polarization information in order to reflect the nature of radio frequency waves more effectively in signal processing. Polarization is the direction of an electric field in space. Polarization includes linear and circular ones. Linearly polarized wave is a polarization in which the electric field always exists in one plane, while circularly polarized wave is a polarization in which the electric field rotates along propagation. We measure vital signals by transmitting microwaves to a human body and receiving backscattering from it. In this situation, we assume that the polarization information reflecting the subject's body shape and movement is different for each subject and expect that the separation performance is improved by processing observed signals with the polarization information compared to the case in which only the phase information is used. Experiments demonstrate the effectiveness of the use of polarization.

This thesis is organized as follows. Chapter 2 introduces the MIMO CW radar and the background of conventional ICA. Chapter 3 describes HOT-ICA, which is proposed in this thesis. Chapter 4 shows target location estimation based on measurement physics utilization of HOT-ICA. Chapter 5 presents quaternion HOT-ICA (QHOT-ICA) as a method to see the polarization information of signals processed by HOT-ICA. Finally, Chapter 6 concludes this thesis.