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Review Article

Justifications for Dual-Modality of Ultrasound - Millimeter Wave Holography for Clinical Imaging Applications

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Abstract

Background: Medical imaging increasingly requires multimodal approaches to capture complementary tissue information. Ultrasound (US) provides excellent soft tissue contrast and penetration depth, while millimeter-wave (mm-wave) imaging offers high-resolution surface and subsurface dielectric property mapping. Both modalities can employ holographic techniques for three-dimensional reconstruction. **Objective:** To propose a unified theoretical framework for combining US and mm-wave holography in a single contactless imaging system for medical applications, with particular emphasis on musculoskeletal imaging and foreign body detection. **Methods:** We present a conceptual design, utilizing the Double Circular Scan (DCS) format for both modalities, enabling synchronized data acquisition and real-time image reconstruction. The system employs non-contact US probes with saline coupling and integrated mm-wave transceivers operating at 30-100 GHz. Mathematical modeling demonstrates theoretical resolution capabilities and image reconstruction algorithms based on Fast Fourier Transform (FFT) techniques.**Results:** Theoretical analysis indicates that the DCS format can achieve spatial resolutions of approximately half wavelength ($\lambda/2$) for both modalities, with US providing penetration depths of several centimeters, while mm-waves are offering sub-millimeter surface resolution. The unified scanning approach enables pixel-level fusion of mechanical (US) and dielectric (mm-wave) tissue properties. **Conclusions:** This technical framework presents a novel approach to multimodal medical imaging that could enhance diagnostic capabilities in orthopedics, oncology, and emergency medicine. Future work should focus on prototype development and clinical validation studies.

Keywords: Multimodal imaging; Medical holography; Non-contact ultrasound; Millimeter-wave imaging

Introduction

The evolution of medical imaging increasingly demands multimodal approaches that combine complementary information from different physical phenomena. This paper presents a theoretical framework for integrating ultrasound (US) and millimeter-wave (mm-wave) holographic imaging into a unified medical imaging system. This combination leverages the deep tissue penetration of ultrasound with the high-resolution surface and subsurface dielectric mapping capabilities of mm-waves.

Rationale for Multimodal Integration

The complementary nature of US and mm-wave imaging makes their combination particularly attractive for medical applications. Ultrasound holography, which has evolved significantly since the pioneering work of Edler and Hertz in establishing echocardiography [1,2] excels in deep tissue penetration of several centimeters, mechanical property assessment including elasticity and density, real-time imaging capability, and maintaining an established clinical safety profile. The theoretical foundations for acoustic holography were established by Marom and colleagues through their work on controlled reference beam phase techniques [3,4] which enabled improved depth discrimination and real-time adaptability in clinical applications. Millimeter-wave holography provides high spatial resolution at the sub-millimeter level, excellent dielectric property contrast, non-ionizing radiation safety, and sensitivity to tissue hydration and composition. The development of mm-wave holography emerged from radar and microwave imaging research, with Farhat's landmark papers formalizing the principles of mm-wave holography including coherent wavefront reconstruction and dielectric imaging [5,6]. These foundational works established mathematical models that underpin today's synthetic aperture and near-field mm-wave systems.

The integration of these modalities addresses current limitations in single-modality imaging, particularly in applications requiring both structural and compositional tissue information. Recent advances in multimodal medical image fusion have demonstrated the value of combining complementary imaging techniques for improved diagnosis [7,8]. The application of deep learning to multimodal fusion, particularly using convolutional neural networks, has shown promise in extracting spatial features from ultrasound while simultaneously mapping dielectric properties from mm-wave data [9,10].

Clinical Context and Applications

Three primary clinical applications drive the development of this combined system. First, foreign body detection presents significant diagnostic challenges, particularly for metal fragments and non-radiopaque materials. The proposed system could detect metallic objects through mm-wave dielectric discontinuities while US provides depth localization, offering advantages over traditional radiographic approaches [11]. Second, musculoskeletal assessment requires comprehensive evaluation of muscle, tendon, and bone through both mechanical and compositional information. The combined system could simultaneously assess tissue stiffness through ultrasound and hydration status through mm-wave imaging, with applications in sports medicine and rehabilitation [12,13]. Third, tumor characterization could benefit from the detection of both mechanical and dielectric property changes in malignant tissues, potentially improving specificity in tumor detection and margin delineation [14].

Theoretical Framework

System Architecture

The proposed system employs a Double Circular Scan (DCS) format, which has been demonstrated to provide superior image quality compared to raster or spiral scanning methods [15]. The DCS format is mathematically described by

$$x = R[\cos(\omega t) + \cos(N\cdot\omega t)] \text{ and } y = R[\sin(\omega t) + \sin(N\cdot\omega t)],$$

where R represents the scan radius (typically 25 cm), ω is the angular velocity (0-250 s^{-1}), and N is the scan line density factor (typically 50-100). This scanning approach offers the advantage of dense simultaneous sampling in both central and peripheral regions of the hologram recording aperture.

Non-Contact Ultrasound Configuration

The US subsystem utilizes a non-contact approach with saline stream coupling, eliminating direct transducer-tissue contact. This configuration, previously validated in dental and orthopedic applications [16,17], offers several advantages including consistent acoustic coupling without operator-dependent pressure, sterile field maintenance in surgical applications, and reduced motion artifacts during scanning. The acoustic beam propagates through a laminar saline stream with a typical distance of 5-10 mm before entering tissue. The system operates at frequencies of 2-10 MHz, balancing penetration depth with resolution, and has been shown to successfully measure trabecular bone properties and detect cortical bone layers within trabecular structures [18,19].

Millimeter-Wave Configuration

The mm-wave subsystem employs transceivers operating at 30-100 GHz, with frequency selection based on specific clinical requirements. Lower frequencies (30-60 GHz) provide deeper penetration of 2-5 mm for subsurface imaging, while higher frequencies (60-100 GHz) offer enhanced resolution of 0.3-1 mm for surface characterization [20]. The interaction of mm-waves with biological tissues is frequency-dependent, with water-rich tissues exhibiting stronger absorption compared to fatty tissues [21,22]. This frequency selection allows optimization for specific clinical applications while maintaining eye-safe power levels below 10 mW/cm^2 as specified by IEEE safety standards.

Holographic Reconstruction

Both modalities employ digital holographic reconstruction based on the Fast Fourier Transform (FFT) of the acquired data, building on the foundational work of Cooley and Tukey [23]. The principles of digital holography have been extensively developed for both ultrasonic and electromagnetic domains [24,25]. For the DCS format, the point spread function demonstrates that this scanning approach produces a sharp central peak with suppressed side lobes, enabling high-quality image reconstruction. The transformation from ultrasound holographic data to visible images can be achieved through various methods including acousto-optical interaction and computer-generated holography [26,27].

Image Resolution Analysis

Theoretical resolution for each modality is determined by the relationship between wavelength, object distance, and aperture diameter. For typical parameters with an aperture diameter of 50 cm and object distance of 20 cm, expected resolutions are approximately 1.2 mm for ultrasound at 5 MHz and 0.2 mm for mm-waves at 60 GHz. These resolution capabilities have been validated in previous studies of both ultrasound holography [28] and mm-wave imaging systems [29].

Data Fusion Strategy

Registration and Alignment

Since both modalities use the same DCS mechanical platform, spatial registration is inherently maintained. Temporal synchronization is achieved through hardware triggering for simultaneous data acquisition, time-stamped data storage for post-processing alignment, and a common coordinate system referenced to the DCS center. This approach builds on established methods for multimodal image registration in medical applications [30].

Fusion Algorithms

The system supports three levels of data fusion as described in recent multimodal imaging literature [31,32]. Level 1 - pixel fusion involves direct combination of registered US and mm-wave images with optimized weighting factors for specific applications. Level 2 - feature fusion extracts and combines complementary features including tissue boundaries from US gradient maps and dielectric interfaces from mm-wave phase maps, creating composite feature vectors for classification. Level 3-decision fusion performs independent analysis of each modality followed by probabilistic combination of diagnostic decisions, an approach that has shown promise in AI-driven diagnostic systems [33].

Real-Time Processing Requirements

For clinical viability, the system must achieve data acquisition in less than 1 second per complete scan, reconstruction in less than 2 seconds per modality, fusion and display in less than 1 second, resulting in a total imaging cycle of 5 seconds, or less. These specifications are achievable with current GPU-accelerated processing platforms, as demonstrated in recent real-time holographic imaging implementations [34].

Performance Analysis and Limitations

Theoretical Advantages

The proposed system offers several theoretical advantages, including complementary contrast mechanisms, where mechanical properties - from ultrasound and dielectric properties - from mm-waves, provide orthogonal tissue information. Both modalities are non-ionizing and safe for repeated imaging, unlike X-ray or CT modalities. The non-contact operation reduces infection risk and operator dependency, particularly important in surgical settings [35]. The unified platform with a single scanning mechanism reduces system complexity compared to separate imaging systems.

Technical Challenges

Several technical challenges must be addressed for successful implementation. The penetration depth mismatch between US (several centimeters) and mm-waves (few millimeters) requires careful consideration in fusion algorithm design. The order-of-magnitude difference in spatial resolution between the modalities necessitates sophisticated interpolation and registration techniques. Both modalities experience tissue-dependent and frequency-dependent absorption that must be compensated [36]. The DCS scanning time of about 1 seconds requires motion compensation strategies for imaging tissues or organs.

Safety Considerations

Both modalities operate within established safety guidelines. For ultrasound, the system maintains a Mechanical Index below 1.9 and Thermal Index below 6.0, consistent with FDA guidelines for diagnostic ultrasound [37]. For mm-waves, power density is maintained below 10 mW/cm² in accordance with IEEE C95.1 standards for radiofrequency exposure [38].

Clinical Implementation Pathway

Prototype Development Phases

The development pathway consists of three phases. Phase 1, representing the current stage, focuses on mathematical modeling and simulation, individual subsystem validation, and phantom studies to demonstrate proof of concept. Phase 2 will involve system integration including combined hardware platform development, real-time data acquisition and fusion implementation, and performance optimization. Phase 3 will encompass clinical validation through IRB-approved pilot studies, comparison with standard imaging modalities, and clinical workflow integration.

Proposed Clinical Studies

Three primary clinical studies are proposed for initial validation. A foreign body detection study will compare sensitivity and specificity versus CT and radiography, with focus on non-radiopaque materials in emergency department settings. This application is particularly relevant given the limitations of current imaging modalities in detecting certain foreign materials [39]. A musculoskeletal assessment study will evaluate applications in athlete monitoring and injury prevention, prosthetic fitting evaluation, and rehabilitation progress tracking, building on established uses of ultrasound in sports medicine [40]. A tumor margin delineation study will assess feasibility for intraoperative guidance, comparing results with frozen section analysis and evaluating negative margin rates, addressing the critical need for real-time intraoperative imaging [41].

Discussion

This technical framework presents a novel approach to medical imaging that combines the complementary strengths of ultrasound and millimeter-wave holography. The unified DCS scanning format enables efficient data acquisition while maintaining spatial registration between modalities. The theoretical analysis demonstrates that sub-millimeter resolution is achievable with mm-waves, while ultrasound provides the necessary penetration depth for deep tissue imaging. The non-contact operation of both subsystems addresses important clinical needs, particularly in sterile surgical environments and when examining sensitive tissues. The potential clinical applications are substantial. In orthopedics, the system could provide comprehensive assessment of both bone mechanical properties through ultrasound and soft tissue hydration through mm-waves, valuable for monitoring healing and detecting early complications [42]. In oncology, the combination of mechanical and dielectric property mapping could improve tumor characterization and margin assessment, potentially reducing re-excision rates [43]. In emergency medicine, rapid non-contact imaging of trauma patients could detect both superficial and deep foreign bodies without radiation exposure [44]. However, several challenges must be addressed before clinical implementation. The disparity in penetration depths and resolutions requires sophisticated fusion algorithms that appropriately weight each modality's contribution based on the specific clinical question. The relatively long acquisition time of more than 1 second may limit applications in dynamic imaging scenarios such as cardiac or respiratory imaging. Cost considerations will be important, as the system requires both ultrasound and mm-wave components plus sophisticated processing capabilities.

Future development should focus on several key areas. Optimization of the DCS parameters for specific clinical applications will be essential, as different scanning speeds and densities may be optimal for different tissue types or pathologies. Development of application-specific fusion algorithms that leverage machine learning (ML) approaches could improve diagnostic accuracy [45]. Integration with existing clinical imaging workflows and PACS systems will be crucial for clinical adoption. A comprehensive cost-benefit analysis compared to current standard-of-care imaging modalities, will be necessary to justify the investment in this new technology. The relationship to existing multimodal imaging approaches should also be considered. While MRI-ultrasound fusion has shown success in prostate imaging [46] and PET-CT has become standard in oncology [47]. The proposed US-mm-wave combination offers unique advantages including real-time imaging capability, non-ionizing radiation, and potential for portable implementation. The system could complement rather than replace existing modalities, filling specific clinical niches where the combination of mechanical and dielectric information provides unique diagnostic value.

Conclusions

We have presented a comprehensive theoretical framework for combining ultrasound and millimeter-wave holography in a unified medical imaging system. The proposed approach leverages the Double Circular Scan format to enable synchronized, non-contact acquisition of complementary tissue information. The theoretical analysis suggests that this combination could provide valuable diagnostic information not available from either modality alone, with particular promise in foreign body detection, musculoskeletal assessment, and tumor characterization. While significant technical challenges remain, including resolution matching, penetration depth disparities, and real-time processing requirements, the potential clinical benefits justify continued development efforts. The non-contact operation, absence of ionizing radiation, and complementary tissue information could address unmet clinical needs in multiple medical specialties. This conceptual framework provides a foundation for future experimental validation and clinical translation. Success will require interdisciplinary collaboration between biomedical engineers, medical physicists, radiologists, and clinicians to optimize system design for specific clinical applications. Initial prototype development and phantom validation studies are the logical next steps, followed by carefully designed clinical trials to demonstrate safety and efficacy. The evolution from concept to clinical implementation will likely require several years of development and validation. However, the growing emphasis on personalized medicine and multimodal imaging suggests that integrated approaches like the one proposed here represent the future of medical imaging. By combining the established strengths of ultrasound with the emerging capabilities of mm-wave imaging, this framework offers a pathway toward more comprehensive and accurate tissue characterization for improved clinical decision-making.

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