Non-Contact Laser Ultrasound (NCLUS) for Medical Imaging and Diagnosis

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CLRC

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Potential of Non-Contact Laser Ultrasound (NCLUS)

**First Responders**
- Internal Injuries and Bleeding
- Organ Damage
- Image Through Burned Skin

**Medical Imaging**
- High Resolution
- Mitigate Operator Variability
- Tumor Progression
- Elastography

**Sports Field Medicine**
- Concussions
- Musculoskeletal Injuries
- Traumatized Areas

**Surgical Assessment**
- Open Body Imaging
- Surgical Guidance and Feedback
- Significant Standoff

Medical needs warrant invention and development of *contact-free* internal imaging technologies
## State-of-Art Medical Imaging Tools

<table>
<thead>
<tr>
<th>Magnetic Resonance Imaging (MRI)</th>
<th>PROS</th>
<th>CONS</th>
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</thead>
<tbody>
<tr>
<td>• High resolution</td>
<td></td>
<td>• Large, expensive, in-hospital</td>
</tr>
<tr>
<td>• Safe</td>
<td></td>
<td>• Danger from metal debris</td>
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<tr>
<td>• Fixed reference gantry – enables time image progression monitoring</td>
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<tr>
<th>Computerized Tomography (CAT Scan)</th>
<th>PROS</th>
<th>CONS</th>
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<td>• Fixed reference gantry – enables time image progression monitoring</td>
<td></td>
<td>• Weak on tissue contrasts</td>
</tr>
<tr>
<td>• Radiation risk</td>
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<table>
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<tr>
<th>Ultrasound</th>
<th>PROS</th>
<th>CONS</th>
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<tbody>
<tr>
<td>• High resolution</td>
<td></td>
<td>• Image distortion from <em>inter-observer variability</em></td>
</tr>
<tr>
<td>• Portable, Inexpensive</td>
<td></td>
<td>• No fixed reference</td>
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<tr>
<td>• Safe</td>
<td></td>
<td>• Impractical for time progression imaging in many applications</td>
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<tr>
<td>• In-hospital and field-forward</td>
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NCLUS Concept and Advantages

**Standoff Laser Ultrasound System Concept**

**Benefits over Contact Ultrasound**
- Potential to mitigate *inter-operator variability*
- Inch to 10 meter standoff
- Minimal interference in emergency and surgical settings
- Applicable to burned skin, traumatized areas, open surgical regions
- No repetitive strain
- Reduces infection risk

**Capabilities in Medicine**
- Anatomical Imaging
- Elastography: in-vivo tissue/bone property mapping
- Simultaneous measurement of compressional and shear waves
NCLUS Demonstration System

### Optical Sources
*(ultrasound generation)*

- **Continuum Panther – Q switched Laser**
  - pulse: 7 nS
  - wavelength: 215 - 2550 nm

- **BKtel– Q switched Fiber Laser**
  - pulse: 300 pS - 10 nS
  - wavelength: 1550 nm

### Lincoln Biomedical Laser Doppler Vibrometer (LDV)
*(ultrasound measurement)*

- **Path Length**: \( L(t) = L_{\text{avg}} - d(t) \)
- **Backscattered Wave (Frequency Modulated)**
- **Target Advancing**
- **Target Receding**
- **Target Advancing**

- **Displacement**: \( d(t) \)

**Vibrating Skin**
MIT LL Biomedical Laser Doppler Vibrometer

Monostatic Laser Doppler Vibrometer

Medical Imaging Requirements

- BW: 0.1 – 10 MHz
- Spot Size: ~ 0.1-2 mm
- NEVV: 1-10 μm/sec/rtHz
- Eye Safe: 1550 nm

MIT LL developing custom standoff LDV sensor for optical ultrasound that meets eye-safety and needs for medical ultrasound imaging
Non-Contact Laser Ultrasonic Measurement
Direct Transmission Through Beef Sample

Laboratory Setup

Measurement Geometry

Biomedical Laser Vibrometer Measurement

- Total Non-Contact Laser Ultrasound demonstrated using COTs optical excitation and custom MIT LL LDV without sample surface preparation
- Currently refining LDV design to yield optimal ultrasonic return
NCLUS – In-lab 2D Scanning Study System

- Rapid scan excitation laser across sample in x and y
- US sensing measured with LDV or transducer at single location

OPO – Q-switch laser can vary excitation wavelength deep UV – near IR

Bi-static Optical Measurements

2D Fast Steering Mirror

Continuum Panther OPO
7 ns pulses

Steak

LDV or Transducer Receiver

Optical scan

X
2D Image - Off-end Scan Sonogram

- Optical scan excitation
- Tissue / bone phantom

NCLUS 2D Scan
- Waves: direct, refract, reflect
- Bone Surface
- Fixed receiver location

Ultrasonic Wave Types and Particle Motion
- Rayleigh – surface wave
- Compressional, Longitudinal (P)
- Shear, Transverse (S)
- Extension
- Compression
- Up and down (SV)
- Side to side (SH)

Sonogram ‘Events’
- Direct and Refracted waves
- acoustic wave
- Linear moveout (1 way travel)
- Hyperbolic moveout (2 way travel)
- Reflected waves
- Rayleigh wave

Source-receiver spacing

- Wave speed determined by linear moveout slope
- Wave type determined by speed and particle motion direction
Bone Phantom Ultrasonic Wave Analysis

Measurement Configuration

Optical Source Scan (810nm) 100 excitation locations

LDV
1 mm

Transducer
(0.25” diameter)

Phantom
(0.5” thick)

Steel table top

Optical Source Scan
Fixed Transducer Receiver

Optical Source Scan
Fixed LDV Receiver

Ultrasonic Waves

Sonogram shot records rich in ultrasonic wave information – P, S, Rayleigh waves observed
Compressional Wave Imaging

*Compressional waves propagate in tissue and bone*
- Standard for anatomical imaging in the body
- Also measures Doppler for blood flow

Shear Wave Dispersion

*Shear-waves disperse in coagulated blood*
- Detection of Hematomas
- Fluid viscosity increases due to blood coagulation
- Application for TBI, Internal Bleeding, Organ Disease

Elastography

*Measure compressional and shear waves, also surface and guided waves*
- Determine tissue and bone properties in-situ
- Cancerous tumor detection, osteoporosis, stress fracture detection, neuromuscular disease progression
Optical generation of ultrasound produces useful images when measured with LDV or transducers. Total optical scan and measurement made from 1-meter standoff resolves 1-mm object.
NCLUS 3D - Anatomical Imaging
1 mm rods embedded in 1.5” thick steak

2D Horizontal (x-y) Slices In Depth across Rod 1

Raw Time Data

Depth = 19.4 mm (above Rod 1)
20.7 mm (at Rod 1 depth)
22.6 mm (below Rod 1)

Migrated –Depth Conversion

Cross-range (mm) (y)
• 1550 nm light creates the largest eye-safe photo-acoustic yield and highest acoustic SNR
• 2000 nm exhibits drop which may be attributed to ultrasonic attenuation in tissue
Effects of Excitation Laser Spot Size on Acoustic Directivity

- Larger excitation laser spot size sharpens acoustic directivity, improves down-looking SNR, and minimizes ‘out-of-plane’ scattering while reducing optical power well within safety limits.
- Smaller spot size – larger acoustic beam beneficial for generating compression and shear.
NCLUS System Development Plan

Near Term 1-2 years

Standoff Laser Ultrasound System (stand-mounted)

- Fast Steering Mirror
  Programmable - scans excitation beam
- Pulsed Laser (1550nm)
  PA-Ultrasound excitation
- SWIR Camera (700 - 1700nm)
  Registers laser spot locations on skin for fixed reference
- NCLUS Laser Vibrometer (1550nm)
  Ultrasonic return receiver

Tomographic Imaging System (In Progress)

Longer Term 5 years

- NCLUS ‘Optical Tri-Corder’
- Chip-Scale Lidar & Integrated Photonics
  (leverage Lincoln Technology)

  - Q-switched microlaser
  - μlens/APD/CMOS-timing
  - Focal Plane Arrays

Integrated photonics and chip-scale lidar technologies enable motion compensation and miniaturization for hand-held system
Summary

- Demonstrated NCLUS approach can generate measureable ultrasonic signals and images in bio-tissue useful for medical applications
  - Photo-acoustic conversion generates far-field ultrasonic waves
  - Useful optical excitation possible using skin / eye safe power levels
  - Non-contact LDV capable of measuring optically induced ultrasound signal

- Scanning optical excitation yields 2D, 3D ultrasonic images in tissue and bone
  - Optical source can generate full suite of ultrasonic waves
  - Able to resolve 1-mm metal rod in tissue mass

- Currently adapting NCLUS technology to specific medical applications
  - Tomographic imaging – elastography program underway for prosthetic fitting
  - Exploring system for bone health – stress fracture detection and monitoring

- NCLUS system planned for rapid and longer term developments
  - Stand-mounted and hand-held field forward