Photoacoustic Sensing of Explosives (PHASE)

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PHASE technique exploits large stored internal energy of explosives for detection
- Explosives’ acoustic emissions depend critically on optical wavelength and material absorption

Laser vibrometry enables standoff detection (probes explosive emission within millimeters of source)
PHASE Operational Concepts

Rapid Development
Close Proximity Detection

Check-Point Scanning

Robotic – Standoff Cued Sensing

Mobile Scanning for Covert Fabrication

Long Term Development
Scanning from UAV Platform

CONOPS: Cued scans for explosive residue via low altitude airborne platform

• PHASE system components well poised for rapid development for close proximity applications
• UAV platform system requires significant development
Estimated Performance for Vehicle Checkpoint Inspection

**Explosives**
- DNT on various substrates
- RDX on various substrates
- C4 on glass
- TNT 100 $\mu$g/cm$^2$
- TNT 10 $\mu$g/cm$^2$
- TNT 1 $\mu$g/cm$^2$
- HMEs - ANFO, black powder

**Confusors with Fuel Oil**

**Environmental Materials**
- Multiple car panels – (clean and dirty; metal & painted), plastic moldings, handles

- Trace level explosives separate out from clutter and can be detected with reasonable confidence
- ROC analysis suggests very low fill trace detection is challenging against more false alarms

**ROC Analysis**
- 1 detection: Pd = 0.80
- 1 FA in 62 cars $\geq$ 1 $\mu$g/cm$^2$
- 1 FA in 152 cars $\geq$ 10 $\mu$g/cm$^2$
- 2 detections: Pd = 0.80
- 1 FA in 400 cars $\geq$ 1 $\mu$g/cm$^2$
- 1 FA in 441 cars $\geq$ 10 $\mu$g/cm$^2$
## Key Advantages of PHASE Technology

### Current capability (266 nm excitation)
- Either demonstrated or predicted based on similar photochemistry

### Potential capability (213nm excitation)
- Based on known optical absorption at this wavelength

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- Potential for **significantly greater standoff** than other detection methods
- Noise-limited detection against realistic threat = 100 ng/cm$^2$
- Exploits common factor of explosives – stored internal energy
  → **Should be adaptable to evolving threat**
- Acoustic clutter and interference are exceptionally limited
- Single-pulse detection enables potentially rapid area scan rate
- System components have potential to acquire signals from static or moving platforms
1) Discovery of unique explosives signatures in high ultrasound spectrum against very low clutter
2) Laser vibrometry senses and resolves high frequency ultrasound signals from standoff
**PHASE Standoff Measurements**

- Laser vibrometer developed at MIT Lincoln Lab detects explosive residue to 30 meter range
- System development possible to 1 km – UV challenging to keep below skin safety limits
Technical Overview
Photo-Acoustic Excitation

Common Materials

- Pulsed UV
- Temperature vs. Time graph:
  - Ta
  - Tb
  - T1
- Thin:
  - Flexing surface causes acoustic and elastic waves
- Thick:
  - Negligible response
- Man-made:
  - Ablation common

Explosive Materials

- Explosive residue (solid phase)
  - Absorbed photons
  - UV wavelength optimized to maximize absorption
  - Explosive residue (vapor phase conversion)
- High pressure vapor generates acoustic and surface waves

Explosives energy release much greater from pulsed UV excitation compared to common materials.
Photo-Acoustic Sensing using Laser Vibrometry

Laser Vibrometer Measures Doppler Shift

- Laser
- Transmitted Wave
- Backscattered Wave (Frequency Modulated)
- Target Advancing
- Target Receding
- Target Advancing
- Vibrating Surface

Laser-Mic Sensing

- Laser Vibrometer can measure surface vibrations and acoustic waves in the vicinity (near field) of explosives from significant standoff with fine location accuracy (~ 1 cm)

- Vibration Amplitude: Excursion distance on carrier
- Vibration Frequency: Doppler side band

- Compression Modulates Carrier
- Rarefaction Modulates Carrier

Acoustic wave causes temporal index of refraction change
PHASE Demonstration System

Optical Excitation Source
(UV – photoacoustic generation)

Pulsed Laser 266 nm – Deep UV

Laser Doppler Vibrometer (LDV)
(acoustic emission measurement)

Custom – standoff
MIT Lincoln Laboratory

Commercial – lab
Polytec

Laboratory Set-up

Laser Vibrometer

Sample

UV Pulsed Laser

Sample
PHASE Signal Dependence on Optical Absorption and Explosives Energy

- Explosives possess high internal energy – Excitation laser wavelength chosen to match strong optical absorption of explosives
- PHASE acoustic emission signal scales directly with explosives optical absorption

Effects of Optical Absorption / Wavelength on Photoacoustic Emission

- Optical Absorption at 266nm,
- Internal Energy \(\Delta H\)
- Emitted Photoacoustic Power (arb)

PHASE Signal Dependence

- PETN, TATP, KCIO\(_3\)-based, Urea Nitrate
- Military-grade Explosives (TNT, RDX, C4, HMX, …)
- HMTD
- Confusors (fuel oil, …)
- Common materials, substrates

Absorption Cross Section (10\(^{-18}\) cm\(^2\)/molecule)
PHASE demonstrates detection capability down to 100 ng/cm² (5th generation fingerprint).
1. Signal Magnitude
2. Mach Number
3. Waveform Asymmetry

Multiple metrics aid in discrimination of explosives from ordinary materials
- More metrics being investigated via statistical analysis of waveforms
Summary

- Urgent need to develop standoff sensing capabilities to detect explosives that target civilians and military staff
  - Detecting trace level explosives key to finding device

- PHASE innovations include
  - Discovery of high ultrasonic frequency signals resulting from UV excitation
  - Laser vibrometry able to sense and resolve resultant signals

- PHASE demonstrated high sensitivity and long standoff sensing capabilities
  - Signals measured from 100 ng/cm\(^2\) concentration of TNT
  - 30-m standoff measurement achieved with estimates to 100-m reasonable
  - Detection capability demonstration shows potential for screening sensor

- PHASE has potential for commercial platform
  - Light weight, portable, low power, covert, safe system capabilities possible
  - Applications for homeland security and overseas activities
Diversity of Explosives Threats

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| **Nitramines** \( \text{N-NO}_2 \) | **Nitrate Esters** \( \text{O-NO}_2 \) | |
|---------------------------------|-----------------------------|
| 2,4-DNT | PETN | HMTD |
| 2,6-DNT | HMX | TATP |
| DNB | NG | DADP |
| TNT | EGDN | |
| TNB | DNDMB | |
| Tetryl | | |

**Military Use**
- Landmines – anti-personnel and vehicles, artillery rounds
- Covert operations (< 10 kg)
- No military applications

**Terrorist Events**
- Madrid Train
- Brussels Attack
- London 7/7
- Oklahoma City
- Boston Marathon
- African Embassy

**Common Explosives feature** – they yield high pressure and temperature release upon detonation

* C. Wynn (MIT LL) – Laser Based Optical Detection of Explosives CRC Press
Role of Explosives Detection

Detection Modalities

• **Point**
  - Measure and analyze explosives particulates
  - Ion mass and mobility
  - Well established techniques
  - Trace quantity sensing < 1 ng/cm²

• **Standoff (< 1 m)**
  - Laser based measurement approach
  - Spectrographic features
  - Limited techniques
  - Bulk and trace quantity sensing

• **PHASE Standoff (>> 1 m)**
  - Laser based measurement approach
  - Exploits acoustic emissions from explosives
  - Path to detect trace deposits and bulk from significant range

The attack the terrorist network
- Find bomb-making facilities
- Interdict transport
- Identify handlers

Defeat the device
- Route clearance
- Checkpoint screening

Forensics
- Find link to suppliers
- Prosecute

Standoff explosives detection role suffers greatly from threat variations, composition, phenomenology, coverage rate, and difficulty in observing small trace explosive quantity levels.
Photo-Acoustic Sensing of Explosives (PHASE) Concept

Utilize high energy of explosives to achieve detection

- **PHASE laser technique exploits large stored internal energy of explosives as detection mechanism**
- **Explosives acoustic – vibrational emissions critically depend on optical wavelength and absorption**
- **Laser vibrometry enables explosives standoff signature measurement to within millimeters of source**

**Dual-modality Signature Measurement (DNT)**

- **Acoustic (sound) Wave**
- **Surface Vibration**
Explosives Detection Techniques

PHASE utilizes MIT Lincoln laser technologies to provide longer standoff while achieving sensitivity.

**MIT/LL Developing Techniques**

- **Canines**
- **Ion Mobility Spectrometry**
- **Photo-dissociation with induced fluorescence**
- **LWIR Hyperspectral Imaging**
  - Range 5-m
  - Range 10-m
- **Photoacoustic Sensing**

**PHASE - 20**

*Additional techniques exist, e.g., LIBS (now generally considered not useful) and CARS (still being investigated)*
Theoretical Modeling of Photoacoustic Emissions from Explosives

LOW FLUENCE
- Simple heating and deformation
- Generates linear acoustic emission

MODERATE FLUENCE
- Material Ablation begins
- Ablation proportional to PHASE fluence
- Generates non-linear acoustic emission
- Ablation releases sparse plume
- FO etching threshold

HIGH FLUENCE
- Gas Chemistry Dominates
- Very high frequency signal present
- Generates very non-linear signal
- Dense plume interacts in gas phase

- Developed physical model (photo-ablation) and its functionality on experimental parameters (laser fluence)
- Potential for eye-safe system via micropchip laser – 0.3 ns pulse