Motivation

Sensor strategy

Sensor for IC-engine research*

Sensor for gas-turbine exhaust*

Sensor for T in coal-fired power plant

Real-time T for combustion control*

Opportunities

*see student poster
Why Research on Smart Sensors?

- Stanford has pioneered laser-based sensing for combustion systems
- Smart sensors can reduce greenhouse gases in multiple ways

- Facilitate research on new energy conversion technologies
- Expedite development of emerging energy conversion technologies
- Improve energy efficiency of existing technologies

- Research plan: GCEP-designed smart sensors w/collaborations for practical demonstrations
Sensor Strategy: Tunable Diode Laser (TDL) Absorption for Temperature and Gas Composition

Sensing Principle:
- Absorption of laser light by molecular transitions in combustion gases
  - Beer’s law: Transmission = \( I/I_0 = \exp(-k_\nu L) \)
  - Absorption coefficient \( k_\nu = f(\text{temperature, pressure, gas composition}) \)
- Ratio of absorbance on two molecular transitions yields gas temperature
- Measurement of absorbance with temperature yields mole fraction
- Use of additional lasers can yield more species (wavelength-multiplexing)
Wavelength-Multiplexing to Extend Sensing Strategy

- Wavelength-multiplexed, diode-laser sensors for simultaneous, in situ measurement of multiple quantities
  - T, H$_2$O, CO, CO$_2$ demonstrated at Stanford
  - Potentially NO, UHC’s, fuel

- Fiber-optic technology enables multiple measurement locations
  - Fiber optics allows remote location of sensors
  - Fiber switches allow multiple measurements paths for one sensor

- Multiplexed absorption concept pioneered at Stanford
Smart Sensor Research at Stanford University

Opportunity:
- New smart sensors offer the potential for reduced GHG emissions
  - Enabling new innovative energy conversion concepts
  - Expediting development of emerging energy-conversion concepts
  - Improving efficiency and pollutant emissions from existing technologies

Strategy:
- Develop non-intrusive sensors using NIR absorption and fiber technology
- Test sensor concepts with collaborations that enable access to practical engine environments, examples:
  - IC-engines, gas turbines, coal combustors, and new burner concepts
Diode-Laser Sensors for IC-Engine Applications

**Motivation:** Reduce emissions from a major source of GHG

**Challenges:**
- IC-engines have limited optical access and time-varying T and P with soot and droplet scattering
- Rapid time resolution is crucial

**Strategy:**
- Develop novel sensors tailored for IC-engine research

**Examples:**
- **HCCI**
  - Ignition controlled by chemical kinetics (not spark or fuel injection)
  - Careful control of temperature and fuel/air mixture composition needed
- **Hydrogen fueled IC-engines**
Initial Sensor Design for In-cylinder T

- Wavelength-multiplexed laser-based sensor (2 colors for H$_2$O and 1 color off-resonance)
- Perform measurements in an optical research engine to prove sensing concept
Proof-of-Principle Tests @ University of Michigan

- Initial measurement campaign shows promising results
  - Demonstrated feasibility of TDL sensing in IC engines
  - Noise near TDC produced by excess loading of water vapor to intake air
- Potential for significant improvements w/2nd generation sensor design: e.g. line selection to optimize T sensitivity at high P, improved optical engineering to suppress vibration noise,…
- Sensor can be tailored to investigate various engine operation modes and cycles
  - e.g. HCCI, Compression Ignition, Spark Ignition, High-EGR, Supercharged, …
Tests Planned for 2nd Generation T Sensor in Optical Research Engines @ Sandia National Laboratory

- Two state-of-the-art optical engine facilities for sensor validation and test
- Utilize TDL-based T and $X_{H2O}$ sensor to investigate HCCI engine operation
- Sensor goal: Facilitate development of HCCI engines to reduce GHG emissions
Opportunities for Future IC Engine Measurements

- Extend T and P sensing ranges to monitor fired-engine operation
- Investigate other species (CO, CO₂, fuel, UHCs, NO)
- Measure non-uniformities in engine using new TDL concepts
- Utilize advanced TDL schemes for improved SNR (e.g. WMS)
- Monitor at multiple locations: intake, exhaust, in-cylinder
- Extend to Diesel engines

**Impact:** Unique TDL sensors will facilitate development and control of new concept IC-engines

For details see student poster (Mattison)
Gas Temperature Sensor for Stationary Gas Turbine Exhaust

Motivation:
- Innovative *in situ* exhaust sensors could provide engine health data needed to minimize environmental impact
  - Optimizing maintenance schedule for planned load management
  - Optimizing burners for minimal pollutants and GHG emissions

Research Plan:
- Two-color T sensor designed and tested at SU
- Demonstrated in exhaust of a 20MW power generator (collaboration with GE Research Center):
  - Readily extended to multiple paths (tomography)

For details see student poster (Liu)
Gas Temperature Sensor for Coal-Fired Power Plants

Motivation:
- *In situ* sensors can improve combustion efficiency
  - Efficiency increase of 1% reduces GHG by 1% and saves $1M/year in fuel (coal) costs for a 600 MW boiler
  - Path-integrated sensing allows optimization of over-fire-air addition
- Sensors can optimize maintenance
  - Identify burner malfunction from temperature profile

Challenges:
- Long path, nearly opaque, vibration and thermal movement

Strategy:
- Sensors developed at Stanford tested in coal combustors in Colorado and TVA with collaboration with Zolo Technologies:
  - Provides fiber technology to enable practical implementation
  - Provides access to power plants to test measurement concepts
T Sensor Design via H₂O Absorption

- T sensor based on water vapor absorption
- H₂O absorption is strong in combustion gases
  - 4-12% H₂O present in combustion products (depends on coal H₂O content)
  - Nearly 500,000 lines in HITRAN between 1 and 2 μm

Use Stanford design rules to choose multiple water lines for optimal sensor performance in the harsh environment of the coal combustor

- Exploit 1250-1650 nm region with available telecommunications lasers and optical fiber technology
T Sensor Design: H₂O Line Selection

- Coal combustor has long path lengths (10-20 m) and poor transmission
  - Therefore need weak lines (database is not accurate or complete)
- Strategy: Choose 9 suitable lines, scanned by 3 diode lasers
- Need to determine spectroscopic parameters in lab to enable measurements

Example of need for accurate spectroscopic data

- Comparison of HITRAN and SU data
- Lines selected for sensor (A-D)
- Note: A, C missing from HITRAN

Accurate diode laser sensing of temperature requires laboratory measurements of fundamental spectroscopic data
Laboratory Experiments for Quantitative Spectral Data

- Measure line strength versus T to verify E” assignment and provide quantitative S(T), line broadening, and line shift data
- Use multi-pass geometry for accurate measurement of weak lines
- Approach yields substantial improvements to current spectral database
Linestrength Measurements: Example for Line A

- Measure absorbance for known H\textsubscript{2}O in heated cell for S(T)
- Fit to confirm E” assignment and find S(T\textsubscript{0})

\[
S(T) = S(T_0) \frac{Q(T_0)}{Q(T)} \exp \left[ - \frac{hcE''}{k} \left( \frac{1}{T} - \frac{1}{T_0} \right) \right] \times \frac{1 - \exp(-hcE''/kT)}{1 - \exp(-hcE''/kT_0)}
\]

End result: First determination of line strength for this previously unknown hot line
Example Results w/ Nine-Line H$_2$O T Sensor: 220MW Plant

- Multiplex 3 lasers and scan 9 H$_2$O lines
- Valmont coal-fired 220MW power-plant in Colorado (dry coal)
- Boltzmann plot fits one temperature (1500K) with $X_{H_2O} \approx 5.9\%$
- Sensor confirms uniform T in combustor, i.e. well-balanced burners with proper over-fire-air flow
Example Results w/ 2nd Generation Sensor: 280MW Plant (T vs Time w/Multiple Paths)

- TVA: coal-fired power plant
  - 280 MW, tangentially fired
  - Fiber-coupled sensor (multiple locations)
  - Coarse tomography (4X2) of T field

Path5 (SOFA), 10-kHz scan rate, 10-s averaging

Thundershowers begin

Note sensitivity of sensor to intake air/fuel conditions

Success achieved has led to a proposal for a permanent sensor installation to improve combustor efficiency and reduce GHG emissions
Demonstrate Use of T Sensor for Combustion Control

Motivation:
- Reducing the fuel-air equivalence ratio can improve combustor emissions and combustion efficiency
- But fuel lean systems are notoriously unstable
- TDL sensors offer the potential for control strategies to extend lean operating limits

Challenges:
- Poor optical access, high noise/vibration, time-varying transmission, and need for high-speed, real-time sensor

Strategy:
- Develop fast, real-time (2kHz) gas temperature measurement for combustion control
  - Novel wavelength modulation design to enable real-time data analysis
- Test Stanford sensors in practical swirl-stabilized burner
  - Triple annular swirl-stabilized burner at Stanford simulates next-generation gas turbine fuel nozzles
Scanned-Wavelength Modulation with 2f Detection: Facilitates Real-Time T Measurement

- Use of 2f simplifies data analysis ==> *increases measurement bandwidth*
- Development of 2f method for T requires extension of 2f theory
WMS Sensor for Real-Time T@ 2kHz:
Relevant Absorption Theory

The transmission coefficient can be written in terms of the modulation and expanded in a Fourier series:

\[ \tau(\nu + a \cdot \cos(2\pi f t)) = \sum_{k=0}^{\infty} H_k(\nu, a) \cos(k2\pi ft) \]

- The interpretation of 2f signals is simplified for weak absorbances (\(k_\nu L \ll 1\)):
  \[ \tau = \exp(-k_\nu L) \approx 1 - k_\nu L = 1 - S(T)\phi(P, T, X_{H_{2O}})PX_{H_{2O}}L \]
- The 2f Fourier component simplifies as:
  \[ H_2(\nu, a) = -\frac{S \cdot P_i \cdot L}{\pi} \int_{-\pi}^{+\pi} \phi(\nu + a \cdot \cos \theta) \cos 2\theta \cdot d\theta \]
- The ratio of 2f peak heights is used to determine temperature:
  \[ \frac{H_2(\nu_1)}{H_2(\nu_2)} = \frac{S_1}{S_2} \int_{-\pi}^{+\pi} \phi(\nu_1 + a \cdot \cos \theta) \cos 2\theta \cdot d\theta \]
  \[ \frac{H_2(\nu_1)}{H_2(\nu_2)} = \frac{S_1}{S_2} \int_{-\pi}^{+\pi} \phi(\nu_1 + a \cdot \cos \theta) \cos 2\theta \cdot d\theta \]

- Impact: New 2f T-sensor should have broad impact on energy conversion research and technology

**Diagram:**
- 2f Signal vs. Wavelength
- 2f Peak Ratio vs. Temperature
- Ratio of 2f peak height yields gas temperature
Example Results: Sensor Reveals Thermal Acoustic Instability

- First application of TDL sensing in a spray flame
- Quartz duct used to generate natural flame instability
- Power spectrum yields the $T_{rms}$ at the instabilities near 350 and 700 Hz
- Scanned-wavelength 2f sensor shows promise for control applications
Example Results:
First TDL Sensor Control of Swirl-Stabilized Flame

- First application of TDL sensing to stabilize a spray flame
- Naturally unstable flame from finite length flame duct
- Active control of air flow suppresses instability
- Results suggest that the T sensor has good potential as a localized control variable, and could be combined with species concentration sensor

For details see student poster (Li)
Summary of Key Accomplishments – Future Opportunities

Key Accomplishments:

- Innovation and design of unique in-situ sensors based on fiber-coupled near-infrared diode lasers
- Contributions to the NIR H₂O spectral database
- Sensors demonstrated in practical environment with help from collaborators
- Sensors can reduce GHG emissions in multiple ways:
  - Improve fuel efficiency
  - Facilitate R&D of new energy conversion concepts
  - Reduce combustion-generated pollutants

Future Opportunities:

- Extend sensing concept to mid-infrared for fuels and trace gases
- Develop sensors for applications to other energy conversion schemes; e.g. fuel cells
- Continue Stanford’s unique role of sensor innovation, engineering, and transfer to practical combustion systems
Acknowledgements

- Students: Dan Mattison, Xiang Liu, Hejie Li, and Xin Zhou

- Staff: Dr. Dave Davidson and Dr. Jay Jeffries

- Collaborators who enabled sensor tests in practical combustion systems
  - Volker Sick, University of Michigan
  - Dennis Seibers, John Dec, and Dick Steeper, Sandia National Laboratory
  - Mark Woodmansee, GE Global Research Center
  - Andy Sappey, Zolo Technology
  - Ephraim Gutmark, University of Cincinnati with thanks to GE Aircraft Engines (fuel spray concept) and Goodrich Corporation (fuel injector)