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Demonstration of a Prototype Real-Time Gas Sensor Designed for Robotic Deployment

Curtis D. Mowry, Gary C. Tisone, Perry C. Gray, John S. Wagner, and Brian F. Clark

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Demonstration of a Prototype Real-Time Gas Sensor Designed for Robotic Deployment

Curtis D. Mowry
Virtual Intelligence Applications
Albuquerque, NM 87110

Gary C. Tisone
TW Research Associates
Albuquerque, NM 87108

Perry C. Gray, John S. Wagner, Brian F. Clark
Lasers and Computational Initiatives Department
Sandia National Laboratories
P.O. BOX 5800
Albuquerque, NM 87185-1188

Abstract

A prototype, proof-of-concept infrared-based (IR) gas sensor is described and demonstrated. The sensor occupies less than 400 cubic inches and was constructed using "off-the-shelf" components to selectively detect SF_6 gas. It was designed for robotic deployment in applications such as atmospheric plume tracer studies. The optical detection scheme fulfills robotic deployment requirements of small size, rapid response, and ruggedness. Results demonstrate real-time detection (less than 1 second response) of a gas mixture containing 100 ppm of SF_6. The sensor could be customized for other potential (tracer) gases that absorb IR radiation. The sensor was not optimized in this work, however appropriate methods to improve detection limits and decrease size are discussed.

Acknowledgments

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Acronyms and Abbreviations

DC	direct current
i.d.	inside diameter
in.	inch
IR	infrared radiation
mA	milliamps
ms	milliseconds
mV	millivolts
o.d.	outside diameter
ppm	parts per million
psig	pounds per square inch (gauge)
SF_6	sulfur hexafluoride
V	volts

Introduction

A prototype sensor capable of robotic deployment and potentially capable of atmospheric plume tracer studies has been constructed and demonstrated. The sensor occupies less than 400 cubic inches (excluding power supply) and is based upon gaseous absorption of infrared radiation (IR). An optical detection scheme fulfills robotic deployment requirements of small size, rapid response, and ruggedness.

The sensor is potentially capable of detecting a plume of SF_6 gas because it can selectively detect SF_6 in the parts-per-million (ppm) concentration range and in the presence of other gases. The sensor can be modified to detect other potential plume gases that absorb IR.

SF_6 is a well-known tracer gas, and can be tracked using detectors such as an electron capture detector (ECD) or an electrochemical detector (1,2). These detectors suffer respectively from a lack of portability or slow response time. Plume tracing can also be performed using methods of off-line sampling where samples are collected and taken back to the laboratory (3). None of these methods are currently suitable for robotic deployment in which the robot (or its operators) need immediate information on the robot's environment.

This document discusses the design of the sensor and presents results of laboratory tests to determine response time and estimates of detection levels. Improvements that could be implemented in further work are also discussed.

Experimental Details

The following section documents the final sensor design, the hardware, and the test protocol used.

Design

Initial input from Robotics Group members suggested that the sensor should fit within two separate cubes of approximately six inches. For this reason, the starting point was a six-inch optical breadboard. Early absorbance tests suggested that an IR path length of 1 meter would be sufficient for ppm detection limits. To utilize as much of the available space and to optimize the path length, a multi-pass "cell" was designed in which the source and detector were not in the same plane. A top and side view of the final optical design are shown in Figure 1 and Figure 2. In Figure 1 the optical path is also shown using a dotted line. To increase robustness, only one mirror (1" flat) was mounted in an adjustable fashion. The side view (Figure 2) shows that the overall height of the sensor is less than 8 inches, however in practice it is just over 8 inches since the signal cord extends above the detector housing.

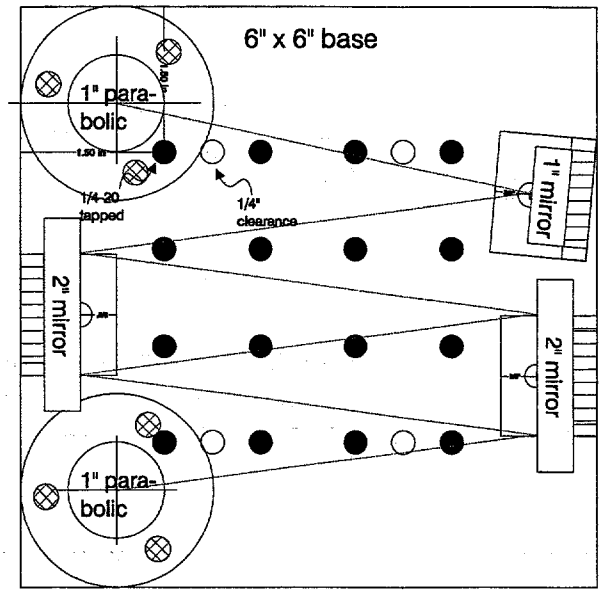


Figure 1: Schematic diagram (top view) of optical portion (breadboard) of real-time gas sensor, including optical path.

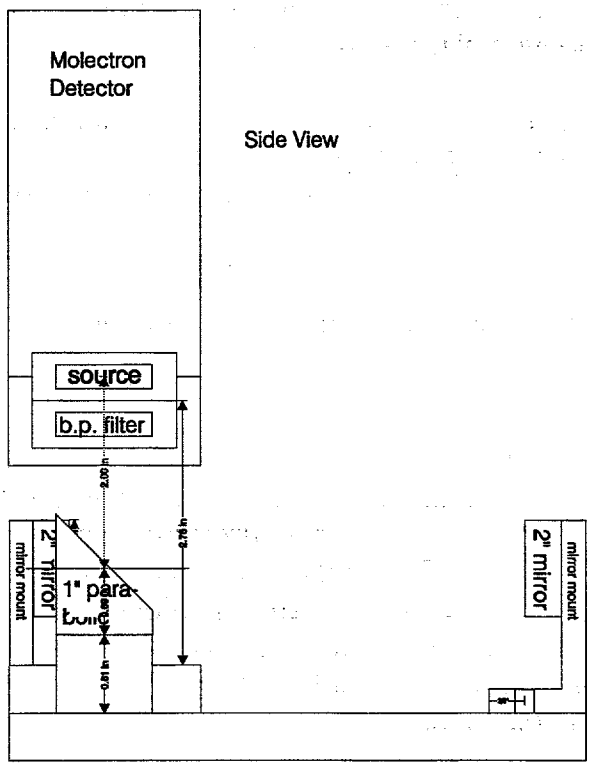


Figure 2: Schematic diagram (side view) of optical portion (breadboard) of real-time gas sensor.

Hardware

All parts are "off-the-shelf" parts from standard manufacturers. All optics are gold coated for good infrared reflectivity.

The lock-in amplifier (model PSD-1, Electrosolutions, Flemington, New Jersey) requires a ±15 volt (V) direct current (DC) power supply rated at 100 milliamps (mA) at each voltage. The manufacturer-specified weight (without connectors or power supply) is 110 grams. The pyroelectric IR detector (model P3-01, Molectron Detector, Inc., Portland, Oregon) is powered by a 9 V battery and provides a DC voltage output. The amplifier was operated using 20 and 40 dB pre- and 20 dB post- signal amplification and was triggered using an "external output" TTL pulse from the IR source. The voltage output of the amplifier was monitored by a strip chart recorder (model 7090A, Hewlett Packard, Palo Alto, California).

Test gases were obtained from Matheson Gas Products (La Porte, Texas) and included 100 ppm SF_6 in nitrogen and pure SF_6.

The IR source and emitter (models CH-60S and CS-IR-21V, Boston Electronics, Brookline, Massachusetts) were driven and modulated by a supply from the same manufacturer (see Figure 3, model CH-60-110). This supply used house electrical (110 V ac) but supplied 15 V dc, 250 mA to the modulator (mechanical chopper) and 5 V dc, 1.0 A to the IR filament. To spatially broaden the emission radiation and refocus it back on the detector, two 1 in. diameter, 90 degree off-axis parabolic mirrors each with a 2 in. focal length (model A8037-106, Janos Technology Inc., Townshend, Vermont) were used. A bandpass filter (model A2184, 1" o.d., 2.29 @ 10.6 µm, Barr Associates, Westford, MA) provides selectivity for SF_6. The gold-coated flat mirrors were manufactured by CVI (Albuquerque, NM). The optical mounts and adjustable mount for the 1x1 flat mirror are standard optical parts obtained from Oriel (Stratford, Connecticut).

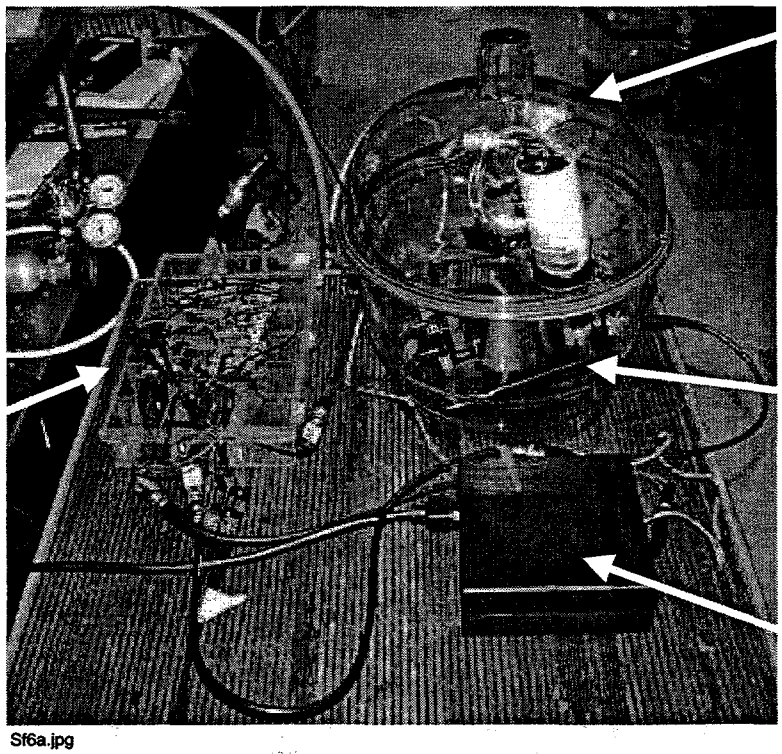
Test Protocol

After the final assembly individual tests pertaining to noise or optical adjustments were performed. During these tests as well as the final demonstration, a standard test protocol was initiated in order to compare the sensor's performance. This consisted of warming up the sensor and electronics for approximately 10 minutes. The chart recorder was then started and allowed to record baseline for 30 seconds, followed by a mechanical block of the beam for another 30 seconds. Blowing SF_6 gas across the optical path of the detector follows another full minute of baseline. The sensor was swept manually with room air until the baseline appeared constant (typically 2 minutes), after which the cover of the test chamber was placed over the sensor. The chamber was evacuated with a vacuum pump to approximately (negative) 10 psig and the chamber was back-filled with the 100 ppm SF_6 gas mixture to approximately atmospheric pressure (the chamber lid was not fastened).

Results and Discussion

General characteristics

A photograph of the sensor and associated electronics is shown in Figure 3. The optical part of the sensor is shown inside the test chamber that was used to contain test gas. All parts were "off-the-shelf" items purchased through standard vendors. The actual IR detector is the white vertical tube inside the test chamber. As described in the Experimental Details section, the breadboard (optical) part of the sensor was 6" by 6" by 8". The only moving part of the system is the optical chopper that modulates the source radiation traversing the sensor. This makes the sensor quite rugged and insensitive to vertical/horizontal orientation.



Sf6a.jpg

Figure 3: Photograph of IR source supply, lock-in amplifier, and breadboard inside test chamber.

SF_6 response and detection issues

Detection properties of the sensor are illustrated in Figure 4, which plots signal intensity (voltage) versus time. In this plot, full-scale voltage is 3 V and the full time scale is 10 minutes, while each grid mark equals 300 mV and 1 minute respectively. As indicated in the figure, the test proceeded in three steps. The beam was first blocked, then SF_6 gas was introduced into the chamber, the chamber was then swept with air and a mixture containing 100 ppm SF_6 was introduced.

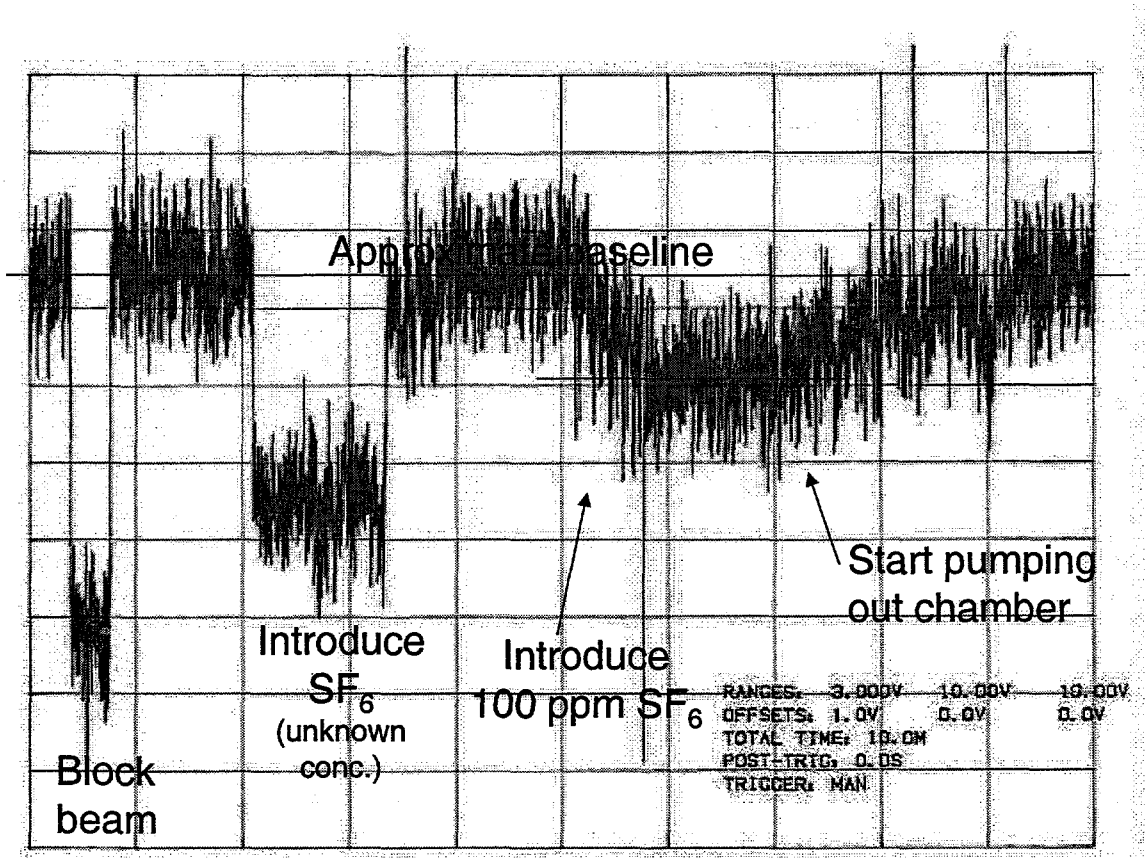


Figure 4: Voltage versus time under different test conditions (see text).

Blocking the beam demonstrates the full dynamic range of the sensor and also shows the response time of the sensor. Without a digitized signal it is difficult to determine an exact response time, however based upon the sound of the chart recorder the response was instantaneous. This response time can be compared to the response upon the introduction of pure SF_6 gas. A comparison of the sensor response for both of these events is plotted in Figure 5. The response to pure SF_6 was instantaneous, and was expected because the limiting factor for absorbance-based detection configured in this way should simply be gas diffusion.

Based upon this test the signal versus gas concentration (or sensitivity) can be estimated. The y-scale in Figure 4 corresponds to 0.88 in. for 300 mV and the signal change for the 100 ppm gas mixture was approximately 1.27 in. This calculates to 4.3 mV per ppm assuming a linear scale. A linear scale would be expected for the dynamic range of the sensor.

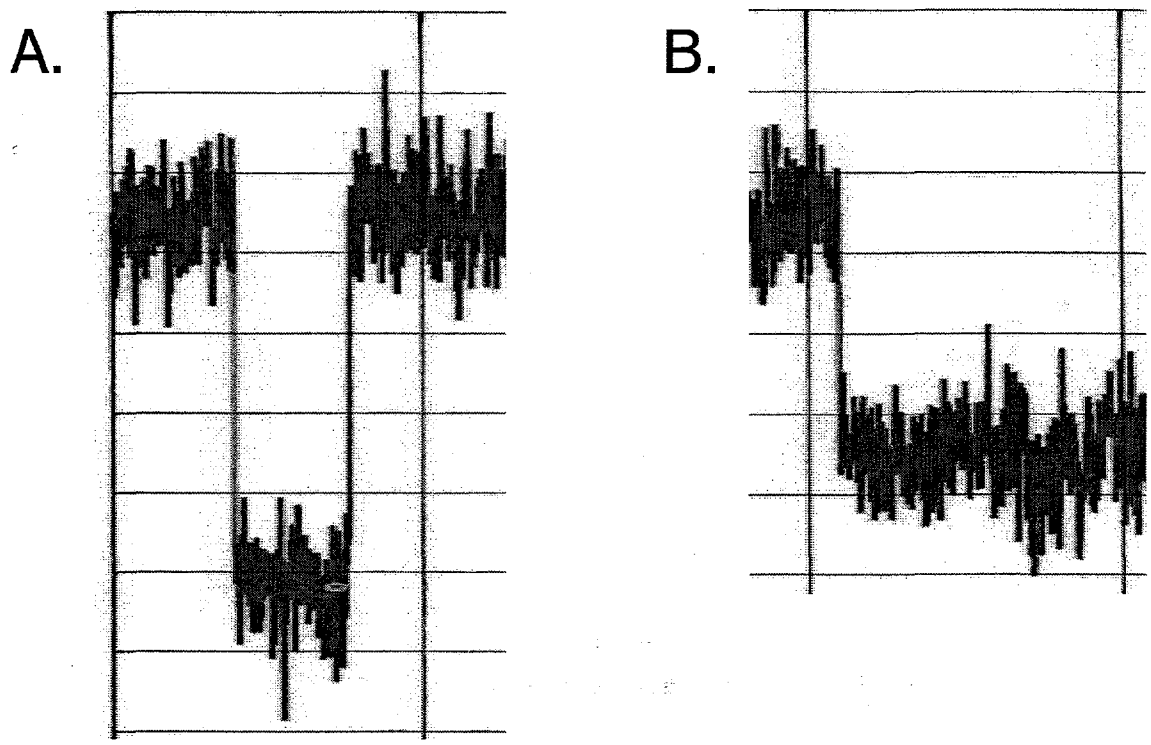


Figure 5: Comparison of response time for A) mechanically blocking beam and B) introducing pure SF_6 gas.

Improvements and Recommendations

The sensor described here was built as a proof-of-concept, and little time was spent optimizing performance. There are several avenues of optimization that could be pursued in the future including signal improvements and miniaturization.

The first priority would be to reduce the amount of noise in the signal. This could be accomplished by using an improved power supply for the lock-in amplifier and improving the electrical isolation between the source, detector, and amplifier.

The simple use of a delay circuit between the IR source and the lock-in amplifier would reduce detection limits. This is because an external output signal from the IR source triggers the lock-in amplifier, however the output of the detector is delayed by approximately 30 ms. Using an adjustable delay generator to optimize the overlap of the detector and amplifier and resulted in a signal increase (for both pure and 100 ppm SF_6 tests) of approximately 30% as observed on an oscilloscope. A delay circuit would achieve this result without increasing the size of the overall sensor.

A brighter IR source would also improve the sensor, providing a larger dynamic range and improved sensitivity. Modulation would be important as well as the output at the wavelength needed for SF_6. Due to the portable-sized nature of the sensor, tradeoffs between power requirements and brightness will likely be

required. Indeed, while this implementation was not truly portable (because some components used house electric), the actual power consumed by the electronics are not unreasonable for robotic deployment. For the detection of other gases (at other IR wavelengths) and reduced power requirements, a different source may be more appropriate.

The greatest opportunity for reducing the size of the sensor, if needed, exists in the commercial IR detector used in the sensor (refer to Figure 3). This detector could be mounted in a different orientation to reduce volume and could easily be modified to a smaller size. Another power source would allow removal of 9V battery as well. The lock-in amplifier could not be reduced in size, however the IR source supply could be reduced in size.

There are two recommendations for further work in this area aside from the improvements mentioned above. Depending upon the gas detection levels needed in a particular application, a brighter source may not be required. For this reason a better knowledge of detection range needed would reduce development costs. Likewise, if lower detection limits were needed, this would be an area to focus effort prior to any miniaturization efforts.

One additional note is that for final deployment signal telemetry would be needed. The signal output is a simple DC voltage and telemetry therefore should not add significantly to the size or power of the deployed package.

Conclusions

A proof-of-concept infrared-based gas sensor, designed for robotic deployment, was constructed out of relatively inexpensive "off-the-shelf" parts. Rapid (less than 1 second) detection of a gas mixture containing 100 ppm of SF_6 was demonstrated. The optics and electronics allow the sensor to be insensitive to vibration or orientation which are important factors in robotic deployment. Depending upon the application, the sensor could be customized for other infrared-absorbing gases. While this demonstration was successful, there are clear avenues of development that would improve the sensor with respect to signal-to-noise ratio, dynamic range, and detection limits. The size of the sensor could also be decreased if needed. The improvements discussed could be achieved without significant development costs.

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