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Imaging of methane gas using a scanning, open-path laser system

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Abstract. We have developed an imaging system for the detection and visualization of methane gas leaks. The system is based on a distributed feedback InGaAs laser diode emitting at 1.65 μm, the beam from which is directed at neighbouring objects. The backscattered light is collected by a Fresnel lens and the gas concentration is deduced from the reduction in collected intensity as measured using a second derivative wavelength modulation technique. The incident laser and the collected beam are both scanned over an area to form an image of the gas emission. To ease the task of locating the source of the emission, we combine the resulting low-resolution image of the gas emission with a high-resolution colour image of the scene. Our results show that the system can image a gas cloud of 1 mm effective thickness at a range of several metres, sufficient to detect a gas leak of 1 litre min^{-1} in light to moderate winds.

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Contents

1. Introduction

Low-cost portable systems for detecting and locating methane gas have wide use amongst the gas utility companies for routine inspection of leaks from pipelines and storage facilities, and for leak-report response applications. Leak detection can reduce product loss, minimize safety concerns and ensure compliance with environmental regulations.

The conventional approach to low-level (ppm) leak detection is based upon flame ionization detectors [1], but such technology measures concentration at only a single point. Such point measurements make locating the source of a leak a difficult and slow process. This becomes even more problematic if the leak is associated with above ground pipe-work, which is difficult to access. When trying to locate the source of a leak, the spatial distribution of the gas cloud is more informative than the precise measurement of concentration at a single point.

Two main approaches exist for gas imaging: active imaging based on optical absorption of laser light and passive imaging using ambient background radiation. For example, Differential Absorption LIDAR (DIAL) instruments, which actively monitor gas using pulsed laser light, have been reported [2]. Such systems can detect gas over the line-of-sight of the light beam using the light backscattered from the gas to give concentration (from the signal size) and range (from the delay time). However, the depth resolution of such systems is not suited to the short (10–20 m) distance scales for local leak detection. Alternatively, we use the backscattered light arising from an object or surface behind the inspection region. This gives a stronger signal but at the expense of losing the range information. However, we have found that operators are able to deduce as much range information as they need, when images are provided. Other examples of active imaging include backscatter absorption [3, 4] and differential backscatter absorption [5]. These systems can detect gas distributions by illuminating a scene using IR laser radiation and imaging the dark region arising from the attenuation of the backscattered light. Passive systems for imaging gas leaks have been demonstrated using IR cameras employing outdoor thermal background radiation [6]. However, the sensitivity of passive systems is particularly susceptible to variations in background temperature, which at certain time during the daily cycle may reduce the sensitivity of the instrument to zero.

Methane gas has its strongest absorption in the 3 μm spectral region. An imaging system based on an optical parametric oscillator (OPO), operating at 3.27 μm, has been reported by Stothard *et al* [7]. Such systems have the sensitivity and image framing required for the resolution of plume motion. However, most of the corresponding laser sources, such as cryogenically cooled laser diodes and OPOs, exceed the cost budget for a routine inspection device. In addition, the 3 μm waveband is strongly absorbed by vegetation meaning that the backscattered light from such cannot be relied upon to give an adequate light level. Methane also has an absorption band at 1.6 μm for which OPO devices can also be operated [8]. However, this line, although over one order-of-magnitude weaker, also coincides with the single-frequency emission wavelength of low-cost InGaAs distributed feedback laser diodes [9], of the type we use here.

Open path, hand-held, methane detection systems which use distributed feedback InGaAs laser diodes at 1.65 μm have previously been reported by ourselves [10] and other groups [11, 12]. Our system can measure methane at a range of several metres with sensitivity close to that required for detecting the atmospheric background of 1.6 ppm, with a response time of 100 ms. We have now adapted this approach by incorporating the sensor into a gas imaging system that scans a laser beam, and sensor field of view, over a region of interest and measures gas concentration using the backscattered light. By combining the gas measurements with a colour camera image, the size and orientation of the plume are evident through comparison with background objects that appear in the image. We have found that gas sources can be successfully located even when the gas image is over an order of magnitude lower resolution than the camera image. Re-sampling and smoothing the low-resolution gas image obtained from the scanning IR laser beam, before superimposing on to a camera image, provides the operator with a clear indication of leak position and concentration. It is important to appreciate that unlike a point sensor, which measures concentration, an open-path optical system measures the integrated concentration (ppm m) over the line of sight. By placing a sealed sample cell within the beam path, we note that the measured linewidth is solely a function of the total gas pressure, rather than the partial pressure of methane. Consequently, within our work it is valid to express the total gas signal as an integrated thickness of pure gas equivalent. i.e 1000 ppm m = 1 mm gas. We find that the target user groups readily understand this choice of measurement unit. It has been shown previously that a measurement of 1 mm gas is sufficient to detect a leak of 1 litre min^{-1} in light to moderate winds [13].

2. Experimental configuration

The open-path gas detector is based upon the design of the hand-held system reported previously in [10] and is configured as an optical head containing a InGaAs laser diode, temperature controller, Fresnel collection lens 150 mm in diameter and photodiode. This is coupled to a control box containing the laser driver, lock-in amplifiers and data acquisition electronics. The laser diode package includes the thermoelectric temperature stage, a methane-filled reference photodiode and output beam collimation. The backscattered light is collected by the low-cost acrylic Fresnel lens and focused on to an InGaAs detector with integral amplifier. The wavelength of the laser is current modulated over the methane transition enabling normal wavelength modulation spectroscopy techniques. The signal from the methane-filled reference photodiode is demodulated at 3f and used to give an error signal within a closed loop control, maintaining the diode wavelength at the methane transition. The backscattered light is demodulated both at 1f to give a measure of the backscattered intensity and at 2f to give a signal corresponding to the gas falling within the optical path. Dividing the 2f signal by the 1f signal gives the gas concentration normalized with respect to reflectivity and range of the backscatter surface. Under favourable backscatter conditions (i.e. a near normal clean surface), we obtain an instrument sensitivity of 10 ppm m and 10 Hz bandwidth.

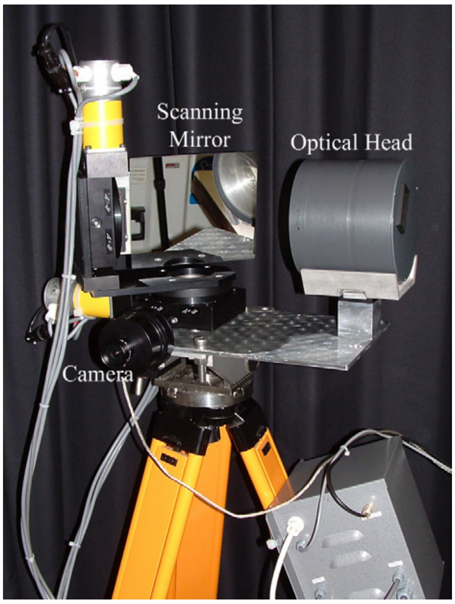

Figure 1. Photograph of the system showing the optical head, scanning mirror and CCD camera.

The whole system is mounted on a tripod. The optical head is fixed with respect to the tripod, the scanning is accomplished using a large scanning mirror, driven by a pair of servomotors under the control of a ruggedized laptop computer. The gas concentration is relayed as an analogue voltage to the laptop, which correlates it to the scanner position. In addition, a colour image is recorded using a CCD camera and relayed to the laptop which combines it with the gas image, allowing the operator to locate the source of the gas leak. Figure 1 shows a photograph of the scanning system.

Clearly there is a relationship between the sensitivity of the gas detection and bandwidth of the measurements, having implications for the frame rate of the imaging system. If we attempted to image the gas cloud at >0.25 million pixels, the frame rate of the system would be unacceptably slow. However, since gas clouds are ill defined, imaging at such high resolutions is unnecessary in leak detection applications. Our gas images are created by performing 10 vertical line scans over the field of view, each taking 1 s with a detection bandwidth of 10 Hz. The resulting gas image, with a resolution equivalent to 10×10 pixels, is re-sampled and smoothed before being combined with the red plane of the colour camera image. This results in a smooth image of the gas leak, shown in red, superimposed with the background image. Figure 2 shows the configuration of the scanning, open-path, laser system.

3. Laboratory characterization

Our initial demonstration was to image an array of Tedlar sample bags (which are transmitting at 1650 nm) containing various gas mixtures, mounted to the door of the laboratory and covering field of view of the detection system. Figure 3 shows an image of five bags, three containing pure methane with a depth of ~5 mm, one containing ~100 mm of 1% methane (equivalent to 1 mm pure gas), and one containing nitrogen. It can be seen that a 1 mm thick cloud of

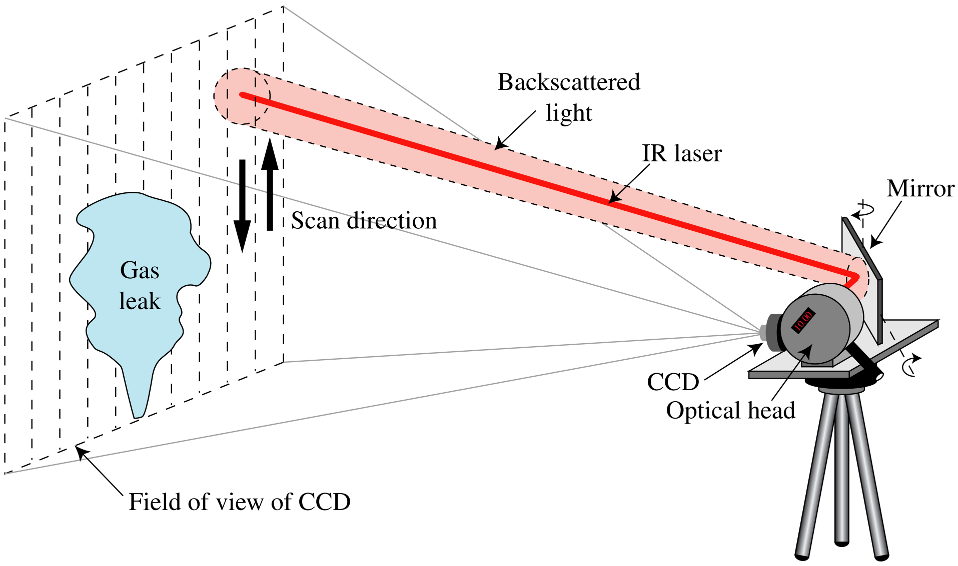

Figure 2. Using a scanning, open-path, laser system to image natural gas leaks.

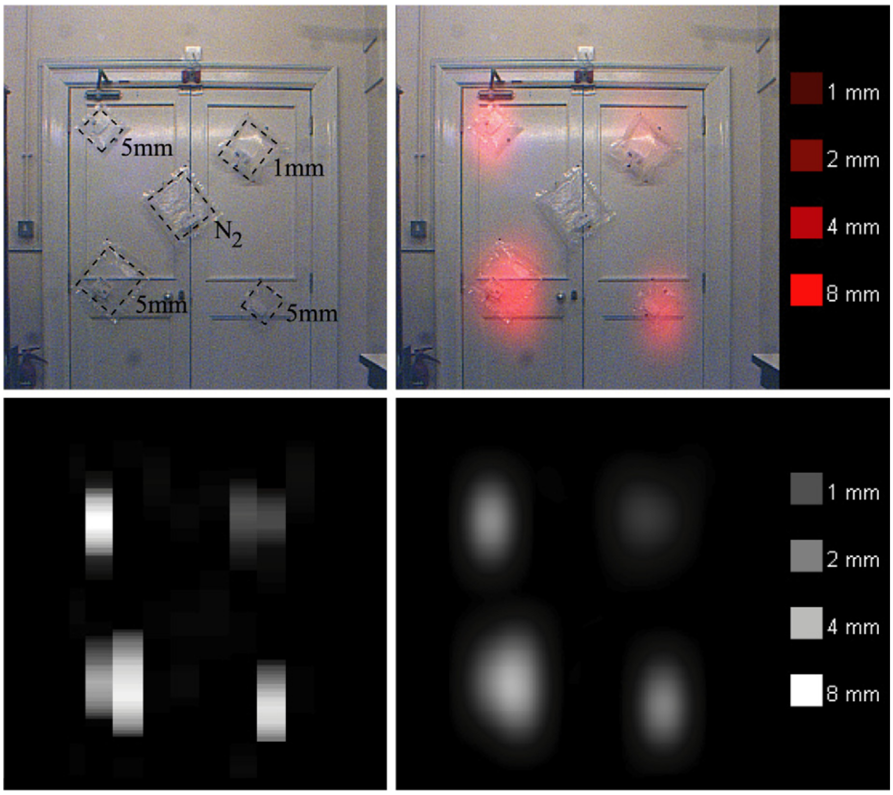

Figure 3. Image of sample bags containing various gas mixtures (top left). Low-resolution gas data (bottom left) is re-sampled and smoothed (bottom right) and combined with the image (top right).

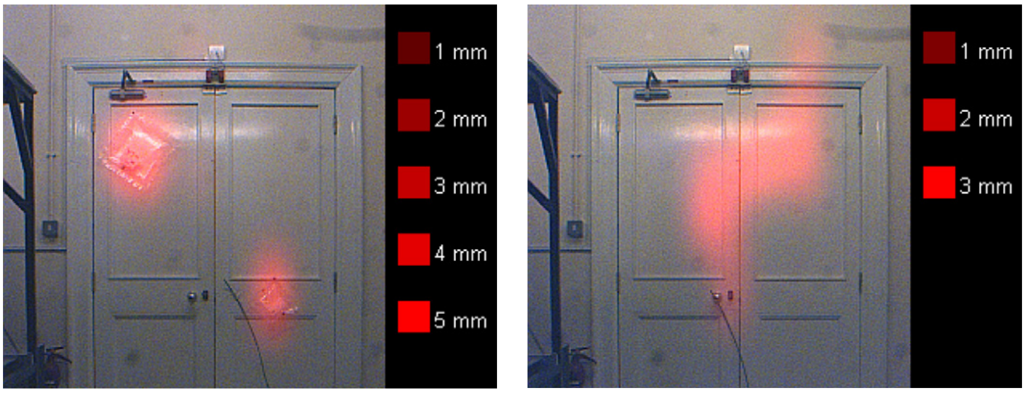

Figure 4. Laboratory characterization: visualization of two sample bags each filled to ∼5 mm gas (left). Visualization of a 1 litre min^{-1} simulated gas leak (right).

methane is easily identified and represents the acceptable lower requirement of the leak detector. By examining areas of the gas image where no sample bag is present we find that the noise equivalent concentration is 0.03 mm = 30 ppm m. It is important to note that the noise equivalent concentration increases when the light is backscattered from a surface which is not normal to the sensor, or has poorer reflectivity.

Subsequently to imaging of the sealed bags a real methane gas source was introduced to the ventilated laboratory. This source was set with a flow rate of 1 litre min^{-1} and coupled to the field of view of the imaging system using a 6 mm pipe.

We created two movies from the images recorded using our system in the laboratory. Figure 4 shows images taken from each of the movies. The first image (see movie 1) is of two Tedlar bags, one 5 litre and one 1 litre, each filled to ∼5mm thickness. The second (see movie 2) image is of a 1 litre min^{-1} simulated gas leak. The original images are updated every 10 s but for ease of viewing the movies are replayed at an increased (×10) frame rate.

4. Field-testing

Most applications for a gas imaging system are out of doors, where the local wind field acts to disperse the gas. As a demonstration, we tested our system outside by imaging methane against a background containing foliage. As before, we created movies using the recorded images. Figure 5 shows images taken from each of the movies. The first image (see movie 3) is of a Tedlar bag filled to 5–10 mm gas. The second image (see movie 4) is of a 1 litre min^{-1} simulated gas leak, delivered via a tube located under the foliage. We recorded a sequence of images (see movie 5) with the gas leak turned off and measured the noise equivalent concentration to be ∼0.5 mm = 500 ppm m. The results, in particular the movies, show that the system is capable of producing useful images of such sources in real-world conditions.

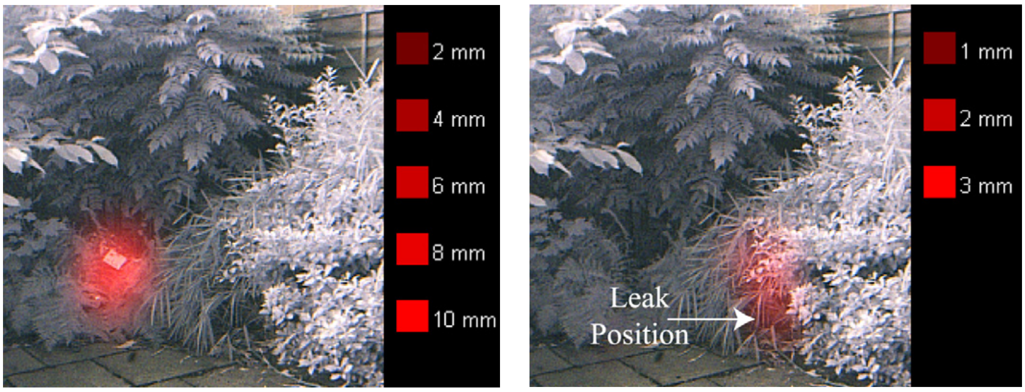

Figure 5. Field characterization: visualization of a sample bag filled to 5–10 mm gas (left). Visualization of a 1 litre $\min^{-1}$ simulated gas leak (right).

5. Discussion

For applications requiring higher frame rates, the system could be modified to use galvanometers, rather than stepper motors like the ones used in our system, to scan the laser and collection optics. As discussed above, there is a relationship between the sensitivity of the gas concentration measurements and the measurement bandwidth. Higher frame rates can therefore be achieved but this is at the expense of poorer signal to noise.

6. Conclusions

We have demonstrated that a scanning, open-path, optical system based on a distributed feedback InGaAs laser diode at 1.65 μm is effective for visualizing methane gas leaks. In order to locate a gas leak, we have found it unnecessary to image the gas at video resolution or frame rate. Our images have an effective resolution of 10×10 pixels, which are then processed and combined with a full resolution camera image. We have demonstrated performance of the system by imaging a gas leak of $\sim$1 litre $\min^{-1}$ outside the laboratory and have shown that there is sufficient 1.6 μm backscattered light to image the leak against a variety of backgrounds including foliage.

Acknowledgment

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References

[1] Simpson C F and Gough T A 1981 Direct quantitative-analysis using flame ionization detection – the construction and performance of the fidoh detector *J. Chromatogr. Sci.* **19** 275–82

[2] Walmsley H L and O'Connor S J 1998 The accuracy and sensitivity of infrared differential absorption lidar measurements of hydrocarbon emissions from process units *Pure Appl. Opt.* **7** 907–25

[3] McRae T G and Kulp T J 1993 Backscatter absorption gas imaging a new technique for gas visualization *Appl. Opt.* **32** 4037–50

[4] Kulp T J, Powers P, Kennedy R and Goers U B 1998 Development of a pulsed backscatter-absorption gas-imaging system and its application to the visualization of natural gas leaks *Appl. Opt.* **37** 3912–22

[5] Powers P E, Kulp T J and Kennedy R 2000 Demonstration of differential backscatter absorption gas imaging *Appl. Opt.* **39** 1440–8

[6] Sandsten J, Weibring P, Edner H and Svanberg S 2000 Real-time gas-correlation imaging employing thermal background radiation *Opt. Express* **6** 92–103

[7] Stothard D J M, Dunn M H and Rae C F 2004 Hyperspectral imaging of gases with a continuous-wave pump-enhanced optical parametric oscillator *Opt. Express* **12** 947–55

[8] Gibson G M, Ebrahimzadeh M, Padgett M J and Dunn M H 1999 Continuous-wave optical parametric oscillator based on periodically poled $KTiOPO_4$ and its application to spectroscopy *Opt. Lett.* **24** 397–9

[9] Temkin H, Tanbunek T, Logan R A, Olsson N A, Sergent M A, Wecht K W and Cebula D A 1990 InGaAs/InP distributed feedback quantum well laser *Appl. Phys. Lett.* **57** 1295–7

[10] van Well B, Murray S, Hodgkinson J, Pride R, Strzoda R, Gibson G and Padgett M 2005 An open-path, hand-held laser system for the detection of methane gas *J. Opt. A: Pure Appl. Opt.* **7** S420–S424

[11] Iseki T, Tai H and Kimura K 2000 A portable remote methane sensor using a tunable diode laser *Meas. Sci. Technol.* **11** 594–602

[12] Wainner R T, Green B D, Allen M G, White M A, Stafford-Evans J and Naper R 2002 Handheld, battery-powered near-IR TDL sensor for stand-off detection of gas and vapour plumes *Appl. Phys.* B **75** 249–54

[13] Hodgkinson J, van Well B, Padgett M and Pride R D 2005 Gas detection using remote laser pointer: interpretation of results *Proc. 5th Int. Conf. on Tunable Diode Laser Absorption Spectroscopy (TDLS-05) (Florence, July 2005)*