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A UAV-based system for detecting natural gas leaks

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Abstract. We describe an integrated system combining an unmanned aerial vehicle (UAV) and open path methane instrument for detecting leaks in natural gas infrastructure. Reducing methane emissions from the natural gas supply chain is a focus of industry and government initiatives to reduce greenhouse gas emissions. UAVs may provide a more cost effective, accurate, and safe approach to finding leaks than existing technology. The base UAV is a 2.3 m wingspan fixed-wing, battery powered autonomous UAV, capable of 90 minute flight time. The methane instrument consists of a tuneable laser diode absorption spectrometer, mounted with a transceiver unit on one winglet, a retro-reflector on the other winglet (path length = 4.6 m), and measurement control boards in the main fuselage. Operationally, the aircraft flies a pre-determined sequence of waypoints downwind of the pipeline or infrastructure. Measured methane concentrations are passed to the UAV flight computer, geotagged, and stored for analysis upon landing. If measured concentrations exceed a certain threshold, a 'loopback routine' in the flight computer directs the UAV to turn around and fly over the methane anomaly to collect additional data. We demonstrate the operation of the system for commercial leak detection in upstream natural gas pipeline networks.

Key words: UAV, drone, methane, natural gas, leaks.

1 Introduction

Methane is a potent greenhouse gas (Saunois et al. 2017) and the dominant component of natural gas. In an effort to reduce greenhouse gas emissions, many governments are interested in policies to reduce methane emissions (e.g., see for Canada: <https://www.canada.ca/en/services/environment/weather/climatechange/climate-action/technical-background-proposed-federal-methane-regulations-oil-gas-sector.html>, accessed 08 September 2017). Although methane emissions are produced from a wide variety of sources, reducing emissions from the natural gas production and pipeline sector is seen as one of the politically easier and more effective targets for near-term emissions reduction; in cases, reducing emissions can be profitable to the operators (Brandt et al. 2016; Saunois et al. 2017; Mayfield et al. 2017; and references therein).

There are a variety of emissions sources in natural gas systems, both intended and unintended. Emissions result from (i) breaks in containment and transport systems that allow pressurized gas to escape, and (ii) abnormal operation of devices that vent gas as part of their operation such as pneumatic valves or hatches on tanks that have been left open in error. Emissions also result from known emissions sources that are operating normally. We refer to the sum of all of the above as ‘leaks’ following the definition presented by Brandt et al. (2016). Leaks are an important target for emissions reduction and a focus of emissions reductions strategies (Mayfield et al. 2017).

Leaks from the natural gas production and pipeline system have several important characteristics. First, the natural gas system covers a large area. Infrastructure is located throughout all major production areas and nearly all major cities. Second, infrastructure is not always easy to access and often lacks road access; pipelines cross fields, mountainous regions, and water bodies. Third, natural gas is generally colourless and odourless in upstream settings, making emissions difficult to quantify. And fourth, studies of leak rates suggest they follow a heavy tailed distribution; there are many small leaks and a few larger leaks (Rella et al. 2015; Yacovitch et al. 2015). For example, in a meta-analysis Brandt et al. (2016) reported that 5% of leaks contribute 50% of total emissions.

These characteristics suggest a specific, ‘large scale screening’ approach could be effective; emissions could be reduced significantly by finding large leaks quickly (Mayfield et al. 2017). The extensive coverage of the infrastructure suggests a mobile platform for sensing could be most effective (e.g., Phillips et al. 2013; see also Kemp et al. 2016 for further analysis). However, as a considerable portion of the infrastructure is remote, aircraft are more desirable than ground vehicles. Because natural gas is difficult to detect and dominantly composed of methane, the common approach is to use specialized methane instruments. The heavy tailed distribution of emissions rates favours an approach where more frequent surveys are performed and large sources are found quickly (Kemp et al. 2016). This distribution also guides the sensor choice: with a focus on large sources, the most sensitive sensors are not necessarily required (Brandt et al. 2016).

Reducing leaks from the natural gas supply chain can be economically advantageous to operators, as the leaking gas represents loss of a saleable product. Additionally, large natural gas leaks are often dangerous, occasionally producing explosions. Although natural gas is dominantly composed of methane, it also contains a wide variety of other hydrocarbons and chemicals, some of which are toxic, carcinogenic (e.g., ‘sour gas’, H_2S), or generally undesirable to vent. Thus, the problem of abating leaks in natural gas supply chains is important among pollution abatement challenges in that there are a wide variety of benefits to the operator. Although the economics are difficult to calculate, it is likely that the majority of leak abatement activities represent attractive investments for operators (Kemp et al. 2016), suggesting that leak abatement may be self-sustaining, even in the absence of new regulations. However, this requires both low cost and robust technology.

Presently used approaches to commercial leak detection use extensive manual inspection with small methane samplers, infrared cameras (Ravikumar et al. 2016), or to a lesser degree, vehicle or aircraft surveys (e.g., Yacovitch et al. 2015) (see Emran et al. 2017 and Ravikumar and Brandt 2017 for additional review). These approaches can have large labour costs (particularly close-range surveys), and have poorly understood effectiveness (e.g., Ravikumar et al. 2016). Aircraft surveys with helicopters and airplanes have been applied, but the high costs favour situations where other

approaches are infeasible, or where a leak would represent a major issue (e.g., large transmission pipelines). Aircraft based infrared absorption spectroscopy has seen some limited scientific application after decades of study (see Frankenberg et al. 2016 and references therein), but has yet to see widespread commercial application. Of particular interest, the analysis of Kemp et al. (2016) examined an array of commonly used leak detection methods, suggesting that automated aerial techniques could provide an important commercial advantage over older methods for leak detection. This analysis suggests there may be promise in examining new methods.

Unmanned Aerial Vehicles (UAVs, or ‘drones’) have seen rapid uptake throughout industrial and atmospheric measurement applications (e.g., Whitehead et al. 2014; Elston et al. 2015; Villa et al. 2016). UAVs can fill many of the roles that manned aircraft previously filled, but at a significantly lower cost. Additionally, UAVs are thought to be safer than manned aircraft (Nesbit et al. 2017), less polluting, less obtrusive to the public, create less interference with the local airflow, and are able to operate at lower altitudes and slower speeds. UAVs can be launched close to the survey location in a small clearing, minimizing airborne mobilization costs. This noted, UAV operations are limited by evolving regulations that differ considerably among jurisdictions. In particular, flying over populated areas is generally not possible presently. UAVs also have short ranges in comparison to aircraft. Despite this, the application of UAVs to natural gas leak detection has been poorly explored. The majority of work has been in the ‘proof of concept’ phase (see Table 1) – significant improvement and advancement towards commercially viable systems is necessary. To effectively scale (and reduce emissions on a larger scale), the technical and scientific challenges associated with commercial viability must be addressed.

Here, we describe a new integrated UAV system for detecting natural gas leaks. The system is designed for low cost commercial application in upstream natural gas production and pipeline settings. The architecture integrates a commercially available fixed-wing UAV with a modified methane instrument. The UAV flies a specified distance downwind from the surveyed infrastructure, measuring in-situ atmospheric methane concentrations (Figure 1). Any leak will create a plume of methane concentrations enhanced above ambient concentrations. If the enhanced concentrations exceed a threshold for investigation, ground crews are notified and sent to a specific location to conduct further investigation, confirm and grade the leak, locate the faulty component, and perform repairs. In this paper, we describe the technology and system integration, describing inherent engineering challenges associated with developing a system for UAV emissions quantification. Purpose built analytics for post-processing the collected data are detailed in forthcoming papers and are not covered here. Additional technical details not covered here are detailed in Myshak and Brown (2016).

2 System design

2.1 UAV

The UAV used in this system is the C-Astral Bramor (hereafter ‘Bramor’). The Bramor is a long range fixed wing UAV (2.3 m wingspan, 3.8 kg nominal take-off weight) driven by lithium polymer batteries and a rear facing drive propeller (Figure 2). The aircraft launches from a catapult and lands with a parachute. It is capable of flights up to 40 km from a base station, up

to 3.5 hr duration when configured correctly. The system used here has a range of approximately 90 minutes. The cruising speed is 15-16 m s⁻¹ (maximum: 23 m s⁻¹). This system was chosen for its capability to house the methane instrument.

To effectively provide leak detection services, large areas need to be covered with minimal downtime. A fixed-wing UAV was chosen to reduce downtime and maximize commercial viability. Although rotary wing UAVs are widely used in other applications, flight times > 30 minutes are difficult to achieve (especially with additional payloads) and the relatively slow airspeeds limit survey distances. Long duration flights are possible with fixed wing UAVs as the payload is carried by lift from the wings; they are also significantly more aerodynamic.

Further, reducing launches and landings by increasing the time the aircraft is in the air is desirable for additional reasons: any time the UAV is close to the ground, there is an elevated potential for collisions, aircraft damage, and often a reduction in ground operator safety. Short flight times necessitate significant numbers of batteries. Charging and maintaining the power supply is expensive, often impractical, and can increase battery fire risk. And finally, the approach of measuring plumes from leaks is sensitive to the atmospheric conditions (e.g., Yacovitch et al. 2015). When conditions are optimum, it is preferable to perform the survey as quickly as possible; launches and landings reduce the time when the UAV is surveying and represent undesirable overhead costs. Although some of these concerns represent infrequent events or inconveniences, over the course of longer term commercial operation, these issues translate directly to costs.

The Bramor UAV is designed for application in beyond visual line of sight (BVLOS) missions, and has been tested at a dedicated facility in Foremost, Alberta, Canada. However, commercial BVLOS missions are presently limited in the US and Canada. This noted, the regulatory situation is evolving rapidly and it is likely that BVLOS flights will be more common into the future. In the meantime, the system can still be operated within line-of-sight (in cases with a mobile ground station) and still be effective for measuring atmospheric methane.

Although the Bramor poses advantages, the catapult launch and parachute landing requires an open area. With experienced operators, a 30-50 m right of way can be used. However, this does limit use of the system in densely forested areas without clearings, and may increase survey time as the UAV may need to be launched away from the survey site. We expand on durability concerns of this specific system in the discussion.

2.2 Methane instrument

The methane instrument used in this system is a modified version of a commercially available open-path tunable laser diode absorption spectrometer constructed by Boreal Laser Inc. (based off their 'Gasfinder 2' technology platform). Specifics of the spectroscopy approach used here are described elsewhere (Silver 1992; Tulip 1995), we provide a summary and discuss the aspects that affect the utility of the system for gas leak detection.

Two major approaches are used in laser spectroscopy of methane with in-situ sensors: (i) open path, and (ii) closed path (see discussion: Detto et al. 2011). Open path sensors have an open laser path that measures the concentrations in free stream air (e.g., McDermitt et al. 2011; Nathan et al. 2015; Tao et al. 2015b). Closed path sensors pull air into a controlled optical cavity to perform measurements. All else equal, laser path length is directly related to measurement precision; longer

path lengths improve precision (McDermitt et al. 2011). Optical path lengths can be much longer in closed path sensors as there are fewer engineering challenges with creating long path lengths in a closed cavity, meaning closed path sensors can be more precise. However, closed path sensors require a pump that uses considerable power to move air through the system, especially if fast response is desired. Generally, fast response is desirable on a UAV as temporal resolution directly relates to spatial resolution. This problem is particularly acute with fixed wing UAVs, where there are minimum airspeed limits to reduce risk of wing stalls. Together, for the tight weight, space, response, and power limitations of a UAV, it is preferable to use an open path sensor.

Laser absorption spectroscopy is a method of measuring the absorption of light in a specific gas, where the general concentration of the gas is proportional to the degree of absorption (Silver 1992; see also Werle 2011). Methane has a strong absorption feature in the near infrared at approximately 1653 nm wavelength. This wavelength of light is invisible to the human eye. To provide a measurement of the methane concentration the system ‘tunes’ the laser wavelength in a sawtooth ramp across the dimensions of the absorption feature by modulating the input current. The returned light is measured by a photodiode, providing an estimate of the degree of absorption (Silver 1992; Tulip 1995). Every 512 measurement ‘sweeps’ across the spectral feature, the average absorption spectrum is compared against an onboard reference spectrum with a linear regression, providing an estimate of the fit between the measured absorption feature and the reference. Corrections for temperature and pressure are applied and a concentration is returned (Tulip 1995; see also McDermitt et al. 2011). Although this is a widely-used technique in spectroscopy, a primary challenge is ensuring the laser is producing the correct wavelength of light. Variations in the physical temperature of the laser can change the wavelength. To address wavelength drift, every 20 measurements a measurement is made of an onboard sealed sample of methane standard with a known spectrum. This allows the control system to re-center the wavelength of the laser on the absorption feature and provides an internal check of the system. The system produces an averaged measurement at approximately 1 Hz.

Although open path systems present many advantages, the precision is limited by the engineering challenges of laser alignment in long path lengths. The standard approach is to use a multiple path optical cell, which requires precision mirror alignment (McDermitt et al. 2011; Tao et al. 2015a, b). In contrast, this system uses a simpler and more robust approach, using the space across the winglets as the optical path. The laser is reflected on a passive retro-reflector, consisting of adhesive retro-reflective tape. As the retro-reflector, by definition, reflects the incident laser light precisely back at the incidence angle there are fewer laser alignment issues. The returned light at the receiver is reflected with a parabolic mirror to concentrate it on a photodiode. The parabolic mirror is sized to match the beam divergence of the laser at approximately 4.6 m, allowing the mirror to capture the majority of returned light. A small amount of light is lost from the laser output hole in the center of the mirror. The use of a retro-reflector means that wing flex does not result in laser misalignment; the angle of the retro-reflective surface can change and the retro-reflector still reflects the light precisely back to the laser. However, it does change the path length slightly in the following manners. First, the path length is reduced slightly as the wing flexes upwards, and the winglets flex inwards. And second, the position on the retro-reflector winglet where the laser is reflected becomes lower as the wings flex upwards (the winglets cant outwards slightly). As measured concentrations are proportional

to path length, and path length changes associated with these two wing flex effects are less than 0.01 m, we consider wing flex effects negligible as the effects on recorded concentrations are typically less than 0.43 %.

To evaluate the precision of the sensor we performed an Allan deviation experiment in the laboratory (Figure 3). This provides an evaluation of the stability of the instrument by measuring the temporal autocorrelation of instrument response in a situation where the variable of interest is constant. We performed the experiment in an isolated calibration room, which had limited air exchange with heating cycles. The path length for this experiment was 4.0 m (slightly less than installed path length), giving a recorded resolution of 0.05 ppmv. Four individual runs were performed, all showed the lowest 1 sigma deviation at time differences of ~ 4 s (depending on exact response frequency). There is variability in the record that is related to pressure, concentration, or temperature changes as the calibration room was not completely controlled. However, this variability is likely to be at timescales > 100 s due to the slow rate of air mixing in the controlled room and typical autocorrelation structure of atmospheric pressure. In natural gas leak detection, the primary stability concern is on the 100 s timescale, as a leak is defined as an anomaly against a running average of measurements. As such, this experiment provides a worst-case evaluation of precision (similar to Tao et al. 2015a). The actual standard deviation is below the recorded resolution of the instrument, suggesting that, in controlled conditions, the instrument is effective at producing sufficiently reproducible measurements for leak detection. Given that the instrument precision is below the recorded resolution, this suggests that any recorded anomaly is likely to be a real feature in the atmospheric methane concentration.

2.3 Software integration and loopback routine

In addition to hardware integration, the software in the methane instrument and Bramor flight control computer was integrated. First, as the methane instrument produces measurements at the internally defined measurement rate (typically ~ 1 Hz), the flight control computer in the Bramor is queried to produce the GNSS location of the aircraft and other relevant flight control parameters. These data are collated with the methane concentration measurement and stored in the memory of the methane instrument. This provides geotagged methane concentration measurements suitable for inverse modelling of the leak location (e.g., Yacovitch et al. 2015).

Second, if the methane instrument records a value above a pre-defined threshold, a special flight routine known as a 'loopback' is triggered (Figure 4; Myshak and Brown 2016). The loopback is a subroutine that brings the UAV back over the anomaly to collect additional data. In practice, any flight pattern can be programmed, but the most common approach used is a 'figure-8' pattern (Figure 4). Such a loopback routine is essential to improve confidence in detecting the presence of a leak and help reduce false positives. Although the primary loopback routine is a figure-8, alternative loopback flight plans can be programmed.

3 Flight demonstrations

Flight demonstrations were undertaken to confirm and demonstrate the operation of the system. These flights demonstrate the typical data that the system collects but do not verify the effectiveness of the system for leak detection. These demonstrations confirm that the system is operational, but don't demonstrate the related leak localization and quantification analytics, which are discussed in a forthcoming manuscript. All flights were undertaken legally with a Special Flight Operations Certificate.

Flight demonstration 1 was undertaken over a Concentrated Animal Feeding Operation (CAFO, or 'feedlot') (Figure 5a, b, c). The atmosphere was unstable with no wind. A series of circular flight paths were implemented over the CAFO. The total flight time was 45 mins. The methane concentrations drifted downwards over the survey (Figure 5b), a result that could be due to changes in the ambient methane concentration in the area. Flight demonstration 2 was an initial engineering test to determine UAV flight characteristics with the mounted methane sensor (Figure 5d, e, f). A series of passes was undertaken in a controlled area. There were no known methane sources in the area. The loops and turns had no effect on the recorded methane time series in both experiments, although some systematic drift was recorded in Flight 1 (Figure 5b, e).

4 Discussion

A number of major challenges exist with developing UAV systems for natural gas leak detection. Here, we discuss the engineering compromises and design considerations that guided development of this system. This discussion helps frame the difficulties in system development.

The flight demonstrations provide some sense of typical data recorded by the system and demonstrate that the system is capable of flying, and different flight manoeuvres (turns, elevation changes) do not modify sensor response appreciably. Recorded methane concentrations are plausible when compared to normal ambient methane concentrations (Saunois et al. 2017). Although the recorded methane concentrations were relatively stable in the air, it is difficult to ensure that flying doesn't modify the sensor response. We cannot be sure that the data recorded by the UAV are accurate or precise without comparison to another sensor. Flying low enough to sample identical air to a ground based sensor, or flying adjacent to an airplane is an attractive possibility, but is unfeasible due to the risks of crashing. Further, the UAV has insufficient payload capacity to carry additional sensors.

There are isolated high and low concentration anomalies that are recorded occasionally in flight data (e.g., see Figure 5b, e). These measurements are not replicated on subsequent passes, providing support for the need for the 'loopback routine' to collect additional data and verify the existence of a plume. There may be issues with sensor drift (see Figure 5b), but this could be a real feature in atmospheric methane concentrations. Regardless, the identification of plumes in operational leak detection is a function of a local spatial and temporal anomaly. As such, the accuracy of the sensor,

including systematic drift in response, is less important. The typical anomalies found for large, important leaks, are often over 2-3 ppmv above ambient concentrations.

The laser path length is a major constraint on the instrument's precision. Most simply, to increase precision, a longer optical path length is required; the increase in precision is approximately linear with path length. However, the precision optical cells required for longer path lengths are less durable, and more subject to laser alignment issues (McDermitt et al. 2011). Consequently, this system provides a compromise in durability and precision. However, it is clear that dramatically increasing the precision of the system will require a redesign of both the spectrometer and aircraft. Larger aircraft platforms may provide longer path lengths, but these platforms would likely raise the cost and limit manoeuvrability relative to the current system.

Generally, fast methane measurement response is desirable. Plumes near to source are often poorly mixed (see empirical data from Nathan et al. 2015), and as such, the spatial dimensions of high concentration tongues of methane are < 10 m wide. With a sample rate of 1 Hz and 15 m s⁻¹ cruise speed, the spatial resolution of measurements is approximately 15 m. Recorded anomalies are likely to be a mix of high concentration and low concentration portions of the measured air, and are likely to be lower than if the sampling rate was faster (or if the UAV was able to fly slower). This general characteristic of close range plumes means that a closed path sensor with slower response (even if much more precise) would further spatially average concentrations and likely be less effective for leak detection. Future investigations will examine the potential for increasing the response rate of the sensor; however, this may carry a penalty of reduced precision as the laser wavelength modulation rate is generally fixed and difficult to modify. However, the increased leak detection sensitivity associated with higher spatial resolution may outweigh the loss in precision.

Durability is a major concern for commercial operation, both in terms of weather conditions and reuse. The Bramor UAV is capable of operating in a wide range of temperatures (-25°C to 45°C) and in high wind (< 15 m s⁻¹), but the nature of gas plumes dictate that it is probably best suited to surveys of leaks during low wind conditions. Damage is a limiting factor for reuse, and in the case of the Bramor, some form of damage is most likely at the end of a survey when the aircraft lands via parachute. Landings have a potential to be rough, depending on the landing terrain. The approach of using retro-reflective tape helps to minimize problems with hard landings affecting laser alignment; however, as an operational consideration, it is preferable to reduce launches and landings to minimize damage risk. Future developments will look to using a hybrid UAV platform that has both rotary wing control and fixed wing endurance. Hybrid UAVs afford greater control during landings, and have the added advantage of hover capabilities for increasing the spatial resolution of measurements in important parts of leak plumes.

In upstream natural gas distribution networks, the specific leak distribution favours systems that can cover large spatial distances and inexpensively screen for large leaks. Targeting these large leaks is an explicit strategy to find the largest, most polluting and economically damaging emissions sources (Kemp et al. 2016; Mayfield et al. 2017). The design of this system reflects this industry need; however, adaptations of the platform to higher precision applications are under present research.

5 Conclusions

We have presented an integrated UAV-based system for locating leaks in upstream natural gas networks. The UAV is a fixed wing, long range, autonomous aircraft with a 2.3 m wingspan. The methane instrument is an open-path laser spectrometer, with the laser path across the winglets of the UAV. The system is designed for commercial application, thus there is an explicit focus on high reliability and risk mitigation. The open path design uses a passive retro-reflector to minimize laser alignment issues and increase durability. This limits precision due to the short path length, but for leak detection in upstream settings, the primary industry need is for fast, inexpensive, detection of large leaks, rather than high precision, high accuracy measurements. Future work will examine methods to both enhance the commercial effectiveness of this system, and adapt the platform for closely related application use cases such as emissions quantification, and higher precision atmospheric chemistry measurement.

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Figure Captions

Figure 1: Basic principle of plume sampling used in this leak detection method. The leak produces a plume of natural gas, which is primarily methane (CH_4). The UAV with onboard (in-situ) sensor must fly within the plume to record an anomaly. Anomalous methane concentrations trigger ground investigation and abatement.

Figure 2: The UAV system and mounting of the methane instrument. (a) The Bramor UAV. (b) The Bramor in launch configuration. A lightweight catapult is necessary during takeoff. (c) The methane instrument uses an infrared laser, which is transmitted through a fiber optic cable to the right winglet, passes across the back of the aircraft, reflected off the opposite winglet, and the response measured with a photodiode. (d) The main control boards that are mounted in the fuselage of the

Bramor. (e) Expanded detail of the transceiver unit, the fiber coupled laser is transmitted through the center of the unit. With a parallel return path from the retroreflector, the return signal reflects off the parabolic mirror and is concentrated on the photodiode.

Figure 3: Allan deviation for 4 separate time-series. These suggest that, in controlled conditions, the instrument is sufficiently precise to isolate anomalies representing leaks.

Figure 4: (a) Software logic to trigger the loopback routine. In the absence of a sufficiently high methane measurement, the UAV will fly along the pre-defined flight path. (b) The loopback routine is typically a ‘figure-8’ pattern over the point where anomalous methane concentrations were recorded. All decisions are made autonomously, but possible to override from the ground control station.

Figure 5: Flight demonstration data from Flight 1 (a, b, c), and Flight 2 (d, e, f). These flights were performed in rural Alberta and demonstrate data characteristics of the system. The figures show the planimetric distribution of concentrations (a, d), a timeseries of concentrations (b, e), and a record of elevation above ground level (AGL) (c, f).

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89x56mm (300 x 300 DPI)

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129x106mm (300 x 300 DPI)

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100x77mm (300 x 300 DPI)

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91x64mm (300 x 300 DPI)

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173x125mm (300 x 300 DPI)

Table 1: Existing small UAV natural gas leak detecting projects with publicly available details and demonstrated flight testing; this project is listed on the bottom. Note that Tao et al. (2015a) did not test on a UAV, but do present a sensor designed for UAV application and test results from a manned aircraft. In-situ sensors record the methane concentrations of the air in-situ to the UAV. Remote sensors record the methane concentrations along some path remote to the UAV (e.g., remote sensing). LiDAR: Light Detection and Ranging.

Study	UAV	Methane sensor
Khan et al. (2012)	Align T-Rex 700E, rotary wing.	Custom, open-path in-situ absorption spectroscopy.
Nathan et al. (2015)	AMR Payload Master 100, fixed wing.	Custom, open-path in-situ absorption spectroscopy.
Neumann et al. (2011, 2013)	Airrobot AR100-B, rotary wing.	Dräger X-am 5600, in-situ metal oxide.
Pergam Technical Services (2015)	rotary wing, various.	Laser Methane Mini, remote differential absorption LiDAR.
Rossi et al. (2014)	rotary wing, various.	in-situ metal oxide.
Emran et al. (2017)	rotary wing, EVO Arm F800-R	Laser Methane Mini, remote differential absorption LiDAR.
This project	C-Astral Bramor, fixed-wing.	Custom, open-path in-situ absorption spectroscopy.