UAV-BASED GAS PIPELINE LEAK DETECTION

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ABSTRACT: Inspection of onshore gas pipelines for gas leaks is an expensive undertaking due to the costs for personnel and equipment. This is particularly true in remote areas. One way to reduce costs is the deployment of small-sized unmanned aerial vehicles (UAVs), which can be operated with minimal deployment infrastructure. However, payload capacities for sensors on these platforms are limited and sophisticated processing is required, in case the system is operated autonomously. This paper describes a payload solution that carries out remote sensing missions using a combination of lasers and an electro-optical sensor to detect gas leaks in unburied onshore pipelines. A camera in the optical wavelength range is utilised to track the pipeline automatically with the actual algorithm running onboard. The extracted position information together with the attitude of the UAV is used to orientate a pair of lasers mounted on a gimbal to sense the pipeline and its immediate surroundings. The corresponding readings can be directly related to the concentration level of the gas, i.e. methane. However, due to the functional principles of lasers, only point-sampling can be achieved. In order to cover the entire pipeline, a whisk-broom scan pattern is generated by controlling the gimbal accordingly. All data is recorded onboard, but can be transmitted to the ground station simultaneously.

1. INTRODUCTION

Large quantities of gas, e.g. methane, are transported daily with the largest portion pumped through pipelines. The so-called mega pipelines can span several thousands of kilometres crossing different terrains onshore and offshore. Driven by the push for energy diversification and reduction of reliance on nuclear power, construction of shorter pipelines is also increasing.

In order to operate the pipeline infrastructure efficiently and safely, regular inspections need to be carried out partially demanded by national law, but also by the operators' interests to reduce financial losses incurred by leaking gas. For example, every year in the USA alone in average 17 fatalities and 68 serious injuries occur due to gas leaks with a total gas emission loss of almost 2% of the overall volume (Woelk, 2013).

The biggest challenge is simply the length and often remoteness of the pipelines that makes the inspection extremely difficult. While vehicle mounted sensing systems are relatively straightforward to operate, they require the availability of a road parallel to the pipeline. This is not always the case as for instance in mountainous or permafrost areas. Otherwise helicopters can be utilised, which cover long pipeline segments in a relative short duration, but which have some limitations in forested areas to get close to the pipeline besides the operational costs. Last but not least, foot patrols are carried out in urban and other complex environments. All these scenarios have their own advantages and disadvantages in terms of costs, flexibility, detection rate, time requirement etc. and there is no ultimate solution, but only situation-driven optimal choices.

Besides the actual platform, the most relevant aspect is the underlying physical principal for the detection. Generally, optical and non-optical methods are differentiated with solutions based on acoustics and flow monitoring as examples for the latter category. While acoustics techniques can determine the location of the gas leak, flow monitoring only can indicate affected segments and requires a second separate inspection for precise leak localisation. A detailed overview on various approached was provide by Sivathanu (2003); Murvay and Silea (2012). Optical methods have the advantage of larger stand-off distances reducing the risk for the inspection personnel. Two main approaches can be differentiated, i.e. passive and active techniques. In case of the latter, the area is illuminated like for instance by a laser. Then a sensor measures absorption and scattering phenomena providing a quantitative measure of the leaking gas (Gao *et al.*, 2006). In recent years, passive systems based on infrared / thermal imaging (Kastek *et al.*, 2008) became more widespread due to the straightforward interpretability of the data by human operators.

In the following, Section 2 will provide an overview of current remotely operated system for gas leak detection together with selected deployed solutions that are of relevance for the described architecture in Section 3. Finally, Section 4 will conclude the paper.

2. CURRENT SYSTEMS

Hereafter only airborne solutions are considered since these provide the maximum degree of flexibility even for remote deployment areas. Both fixed-wing aircraft as well as helicopters are used providing commercial services for leak detection. These piloted aircrafts are equipped with laser or infrared systems, which allow real-time visualisation on-board for an operator. At the same time the data is recorded for later post-mission evaluation. Payload weights easily exceed 150kg, but do not pose any limitation on the chosen platform. Within the group of laser-based sensors, two main concepts can be differentiated, i.e. either the laser scans the pipeline and its surroundings directly (Zirnig *et al.*, 2004) or the laser is deployed in an enclosed cell under the fuselage (Adam, 2014; Banica *et al.*, 2013). The advantage of the latter approach is the higher detection accuracy since the measurement environment is well contained. However, the rotor's downwash can prevent methane plums to enter the instrument in the first place when operated under a helicopter.

Recent projects explored the usage of UAVs for gas detection. For instance, a laser-based sensor, but without flexible scanning was deployed by Zondlo *et al.* (2012). In particular, the focus of the described work was on air quality sensing targeting several different types of gases. In another study the miniaturisation of a laser-based system, which was successfully deployed under a helicopter previously, was addressed (Frish *et al.*, 2013). Finally, acceptance of UAV utilisation received a boost after the deployment of an Aeryon Scout by BP inspecting a stretch of pipeline in Alaska (Krishnamurthy, 2013).

3. PAYLOAD DESIGN

The described solution provides a gas leak detection payload, which can be deployed on different platforms straightforwardly. The design is characterised by a large degree of system independence with limited support requirements. The solution was envisioned to be integrated on different platforms including, but not limited to UAVs. In particular, the following mission scenario was envisioned as the baseline: A low-flying UAV with a ground speed of less than 30km/h operating at an altitude of 30-50m is used to carry out missions of up to 2h duration. Electrical power provision onboard is limited to 5W; higher power demands need to be provided by a battery as part of the payload itself. Maximal payload weight is limited to 5kg. As a first instance, it is assumed that the leak detection is limited to methane with gas temperatures in the range of 5-20˚C transported in a pipeline at a pressure of 1,500psi.

3.1 Platform

The utilisation of a UAV brings the advantage of site accessibility with good visibility of the pipeline. However, not all types of UAVs are equally suitable as platform. In particular the flight dynamics is a crucial selection criterion. Vertical take-off and landing (VTOL) solutions enable deployment in cluttered environments without the need for additional infrastructure and generally allow slower flying speeds in comparison to wing-based solutions. The latter aspect is of operational importance since the UAV is remote controlled and obstacle avoidance is handled by the piloting operator. Moreover, more time over a certain area can be used for repetitive measurements, which eventually leads to higher detection rates and fewer false alarms.

One main trade-off is the size of the UAV. While larger UAVs generally provide more payload capacity, longer mission durations and are less susceptible to turbulences etc., their heavier weight increases handling complexity as well as the risk of damages to the pipeline and other infrastructures in case of unexpected flight events.

In any commercial sensing application a gimbal is required to accommodate the sensors. While a fixed assembly of the sensors to the airframe is less complex, it greatly reduces the use of the sensors since flight path and observation path need to coincide. However, a gimbal installation provides greater flexibility with more degrees of freedom in controlling the location of a data acquisition. Last but not least, active or passive vibration damping is needed to stabilise the sensors from the vibration introduced by the rotors.

3.2 Sensors

As part of this project, two different optical technologies were assessed for their suitability, i.e. imaging-based and laser-based detectors. A comparison of the main differentiators is provided in Table I.

Methane cannot be observed in the visual spectrum of light, but can be detected qualitatively in the images of mid-wave infrared (MWIR) cameras operating in the 3-5µm range. Corresponding cameras are costly and frequently regulated by export control. The detection of gas plumes by humans is intuitive due to the provision of an image, but can be challenging in an actual outdoor environment like for instances in front of complex vegetation.

Moreover, post-processing as it is provided by some cameras based on subtracting subsequent frames (Brown, 2008) can lead to enhanced image interpretation for static observations, but fails for acquisitions obtained by a moving platform. Examples for these observations are depicted in Figure 1. While the plume can be easily detected in the image showing an indoor setting with the gas leaking from a container held in the trial person's right hand, the interpretation of Figure 1(b) is more difficult. At a stand-off distance of approximately 20m the plume was not visually detectable by the operator – neither in the normal nor differential mode (shown). In fact, the good visibility of the moving car on the right side of the image gives an impression on the expected problems when operating in a non-stationary environment. However, it is worthwhile mentioning that gas volumes of actual pipeline leaks have a higher flux than in the conducted experiment, i.e. the detection is expected to be easier.

Table I: Comparison of MWIR imaging and laser-based methane detection approaches

	MWIR imaging	Laser
Acquisition area	Area	Point
Quantitative measurement	No	Yes
Automatic data interpretation	Difficult (for complex scenes)	Very easy
Weight / size	Medium	Small
Costs	Very high	Medium

One of the main advantages of a camera solution is that a larger area can be assessed at any point in time, however, without a quantitative measurement. Examples for off-the-shelf cameras are the FLIR GF320 and the Opgal EyeCGas (Heath, 2011). An airworthy solution is the FLIR Ultra 8000e, which is integrated in a gimbal, but weights 13kg and thus is too heavy for the targeted UAV platform.

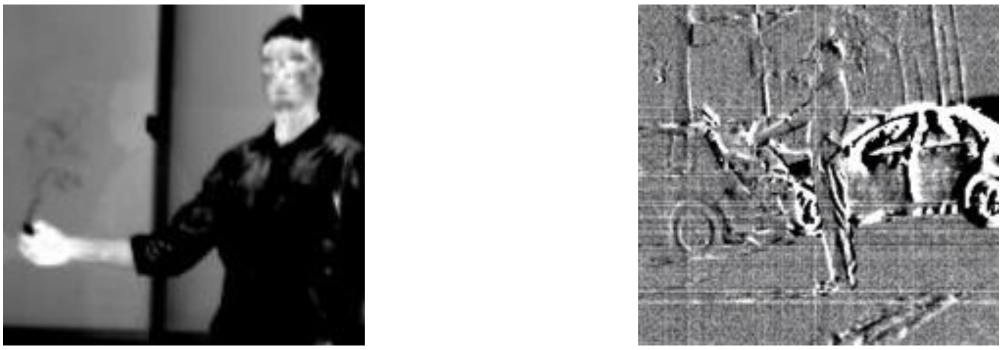
(a) (b)

Figure 1: Examples for small gas plume detections with the FLIR GF320: (a) in an indoor environment with window as background, (b) in an outdoor environment using the differential enhancement mode

Laser-based sensors provide accurate quantitative measurements that can be easily interpreted, i.e. in an unsupervised framework operated by the payload. The main disadvantage is the small sampling area, which is inherent to the measurement principle of a laser. However, the technology is very compact and can be integrated with a UAV straightforwardly. Table II provides a brief overview of a typical sensors' specification.

Table II: Technical specifications of the Laser Methane Mini G

Mechanical specifications
- Dimensions: 70mm × 179mm × 42 mm
- Weight: 600g (including battery)
- Ingress protection: IP65

Environmental specifications
- Operating temperature: -17ºC to 50ºC

Electrical specifications
- Operating time: ~4.5 hrs

Laser specifications
- Target gas: Methane (CH_4)
- Detection limits: 1-50,000 ppm
- Accuracy of detection: ±10%
- Detection distance: 0-100m

Software and communication interface
- Bluetooth link
- Controlled through Android API

In this work, the decision was made for a laser-based solution, i.e. the Laser Methane mini G (LMmG) by Pergam, due to the benefits of low weight, quantitative measurements and the straightforward automatic data interpretation. In order to increase the sampling coverage on the ground, two sensors are used and mounted on a gimbal. While this approach by itself does not achieve dense ground sampling, this is the case when the gimbal is actively controlled to perform a whiskbroom pattern similar to the imaging instrument onboard the Landsat satellite family. For this purpose, an additional optical camera is integrated with the gimbal and the video data analyses in real-time in order to track the pipeline. Finally, the control signals for the gimbal are derived relating the tracked pipeline with the visual green tracking lasers integrated in the LMmG sensors. An example for the scan pattern is shown in Figure 2. Denser sampling in the flight direction can be achieved b reducing the ground speed of the UAV and/or shorter sweeps.

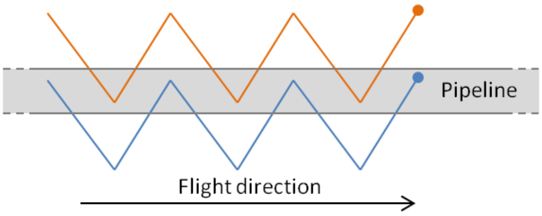

Figure 2: Whiskbroom scan pattern of two laser-based sensors mounted on a gimbal

Theoretically, the optical camera can be replaced by a MWIR camera for detailed post-mission analysis of detected gas leaks. However, in the following this concept is not developed further due to the payload weight limitation of the UAV.

3.3 Data processing

The onboard data processing for the payload comprises video recording for post-mission analysis, recording of the measurements from the sensors, acquisition of telemetry data like GPS for geo-referencing, real-time video analysis in order to track the pipeline, and computation of the control signals for the gimbal. Moreover, the data needs to be interlaced and processed for transmission to the ground control station.

In fact, smartphones are among the most highly integrated embedded systems available on the market today. Especially with an open software architecture like in the Android operating systems, powerful hardware interfaces and integrated communication a smartphone like the Google Nexus 5 suits the given payload weight limitation of 5kg well. More importantly, the phone’s weight of approximately 200g allows physical integration on the gimbal itself. Thus, the built-in camera with optical image stabilisation can be used for the pipeline tracking and cabling is kept to a minimum. The required telemetry data is provided by the smartphone peripherals including data from the integrated GPS, accelerometer and compass. The laser-based methane sensors are interfaces wirelessly through Bluetooth.

The tracking of the pipeline in the video stream is the most computational aspect of above listed processing tasks. Various solutions were proposed for underwater applications (Goyal *et al.*, 2012; Narimani *et al.*, 2009), which are relevant for the tracking of onshore pipelines as well since the scenario and the requirements (piecewise straight segments, constant diameter etc.) are similar. In case a MWIR camera is used then the pipeline tracking is further simplified since the actual pipeline stands out more clearly from the background.

3.4 Communication

Ideally, all acquired data is transmitted back to the ground station in real-time, but in many cases bandwidth limitations in cellular networks restrict the transmission of the video stream. However, this feature is not necessarily needed. In particular, when a camera operating in the visual wavelength range is used, no additional clues can be drawn in terms of leaks and the effective use of a MWIR camera requires a stationary platform behaviour to actually observe the gas plume. Hence, only telemetry and methane sensor data need to be transmitted, which can be handled easily by a GPRS/3G network. If no commercial network is available as it is the case in many remote areas, then a mobile base station can be deployed. Alternatively, data can be interlaced in the UAV’s main communication channel which is used to pilot the vehicle.

3.5 System architecture

The final payload architecture consisting mainly of the two chosen methane sensors (LMmG) and a smartphone integrated on a gimbal is shown in Figure 3. The field-of-view of the camera needs to cover an area including the two green tracking laser points on the ground in order to enable straightforward pipeline tracking. The measurements from the sensors are communicated over Bluetooth to the smartphone, which records all data and transmits relevant data to a remote PC in the ground control station. Both the sensors and the smartphone are powered by their individual integrated batteries.

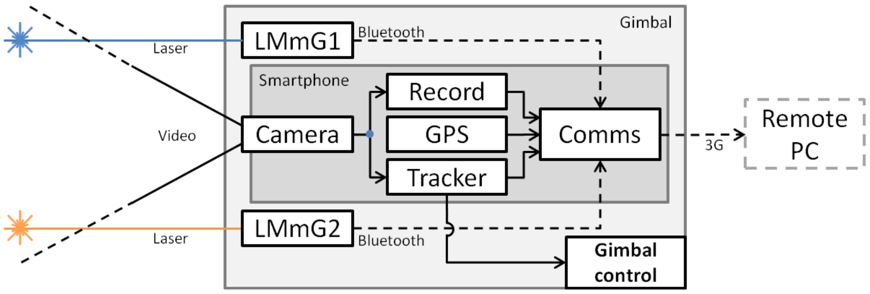

Figure 3: System architecture

4. CONCLUSIONS

It is expected that the number of UAV deployments for pipeline monitoring will increase in the next few years. Driven by increasing pipeline network sizes and cost pressure, the use of manned helicopters is thought to decrease. Initially, savings might not be the main factor, but with the improvement of UAV technology, availability and acceptance will drive the price down. In the same context, integration of easy to operate and cost effective laser-based methane detectors is preferable compared to expensive payloads based on MWIR cameras. Limitations originating from this choice can be mitigated in the design like the suggested whiskbroom scanning approach.

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