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Small-Scale Airborne Platforms for Oil and Gas Pipeline Monitoring and Mapping

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1. INTRODUCTION

1.1 Monitoring oil and gas pipelines

Oil and gas transmission pipelines comprise a network of more than three million km globally (CIA, 2013) that is in continuous expansion (Smith, 2013). Pipeline networks are made up of *legs* of different lengths, up to thousands of kilometres, and can have above- or below-ground configurations. The safety and security of all pipelines, regardless of their size, placement, or location, is of paramount importance to stakeholders and to the public. Proper maintenance of pipeline networks is also important for environmental protection.

Equipment failure such as breakage or leaks can occur for many reasons, including overage of structures and material failure, natural ground movement, accidental *hot-tap*, and third-party interference. Large amounts of oil and gas can be lost following a pipe failure, and more importantly, hydrocarbon leaks can damage the environment through contamination and pollution, seriously affecting ecological health and human security.

Developing and implementing monitoring systems that can continuously assess the state and condition of oil and gas pipelines is essential. Furthermore, monitoring pipeline networks also involves acquiring knowledge of the impact pipelines have on the environment over time, and how they affect vegetation and wildlife.

Traditionally, monitoring pipeline networks has often been restricted to visual inspections or volume and mass balance measurements. Currently, most of the monitoring is still performed using conventional methods, mainly through periodic inspections by foot patrols and aerial surveillance using light aircraft or helicopters. Although ensuring a high level of security, the cost of monitoring methods where there is intensive human involvement in the measurements is also very high. Furthermore, the main disadvantage of the methods used for monitoring and inspection is the potential for late detection of failures, when the output (oil or gas) has been reduced, or the environment has already been affected and damaged.

Some alternative approaches to monitoring pipelines that do not rely on human intervention utilise real-time monitoring systems based on small sensors. These sensors are connected to the pipeline network and can send (via wire or wireless) data to a control centre. However, even wired sensors are vulnerable to damage at any point along the network and wireless sensors' networks can produce ambiguous data, and be unreliable, providing incomplete or inaccurate information (Wan et al. 2012).

1.2 UAV remote sensing

With the advent and progress of remote sensing technology – including sensors and platforms - together with image processing software, new opportunities have emerged for the development of monitoring systems with the possibility for high frequency data collection, that provide a comparatively inexpensive and spatially precise means to identify hydrocarbon leaks. Amongst the most promising techniques, unmanned airborne or aerial vehicles (UAV) provide an important option with a number of advantages over the other more traditional aerial platforms such as light aircraft and helicopters. Such advantages include improved mission safety, flight repeatability, the potential for reduction in operational costs, and fewer weather-related flying limitations (e.g. a UAV can fly below the clouds). These advantages are, however, dependent upon the type and size of airborne platform, sensor type, mission objectives, and the regulatory requirements imposed.

Small-scale airborne platforms, i.e. aircraft with *fixed wing* and helicopters with *rotary wings*, are increasingly being considered as reliable platforms for capturing remotely sensed images for environmental applications, and a low-cost alternative to larger-scale platforms (e.g. ARC, 2003). With recent technological developments (e.g. sensor miniaturization, stabilization and navigation systems) such small-scale platforms provide a powerful basis to gather data and produce information that can be tied to in-situ ground data collection and to large scale satellite imagery, providing a link between multiple spatial scales. Small-scale airborne platforms can therefore provide a very flexible means to acquire unique data and information.

Currently there is a wide range of commercial small-scale airborne platforms available to anyone for the acquisition of low-cost aerial remotely sensed data. These platforms include kites, model aircraft, balloons or blimps, helicopters, Unmanned Aerial Vehicles (UAVs), Unmanned Aerial Systems (UASs), and Drones. Only considering electric UAVs, the total market value is expected to reach over one thousand million dollars by 2023 (IDTechEx, 2014). Many of these small airborne platforms can be equipped with traditional but lightweight versions of single-lens reflex (SLR) or digital cameras, as well as video cameras, for the collection of panchromatic, true colour, and colour infrared photography, as well as digital video footage. The use of camera filters e.g. infra-blue can also enable useful information as the basis for deriving vegetation indices (e.g. Normalised Difference Vegetation Index—NDVI) images for assessment of vegetation condition. Additionally, multi-spectral imagery can also be captured through repeated overflights with the aid of filters—or more recently through the use of on-board multi- or hyper-spectral sensor systems—as well as thermal infrared (TIR), Radar, and LiDAR data. Some of these platforms are also large enough to carry multiple payloads and can use wireless transmissions and video downlinks for real-time data capture, image viewing, and use of *the Cloud* for data storage.

The rapid development of microelectronics and microprocessors, battery technology, GPS and navigation systems, together with reduced costs over the last five years have all helped in triggering an unprecedented demand for, and growth in, the use of UAV platforms for many civilian applications (Watts et al., 2012; Colomina and Molina, 2014). Furthermore, sensor miniaturization has facilitated the collection of a range of spectral and other sensory measurements from small aerial platforms that were not previously possible.

1.3 The report

This report explores the current scientific and non-scientific literature on the use of UAV platforms and sensors that have been used to date for monitoring oil and gas pipelines, with a specific focus on the detection of leaks in oil and gas from onshore pipelines and their effects on the area surrounding the pipeline, such as soil pollution and vegetation stress.

The report will include sections covering the following: 1) a general overview of the characteristics of UAVs; 2) the use of small airborne platforms for oil and gas pipeline monitoring to date with particular attention being paid to the strengths, successes and opportunities, as well as the weaknesses and reasons for the failure of different UAV systems; 3) considerations and developments in the technology of small-scale aerial platforms and sensors specifically tailored to oil and gas pipeline monitoring applications, including battery, sensor, navigation, software, and platform; 4) the legal framework concerning the uses of UAVs as this will have a significant part to play in the future type, scale and use of UAVs; and 5) future prospects for UAV development and application.

2. RATIONALE AND CONTEXT FOR OIL AND GAS PIPELINE MONITORING WITH SMALL-SCALE AIRBORNE PLATFORMS

2.1 Context

Currently there are more than three million kilometres of transmission pipelines carrying hydrocarbons around the world (CIA, 2013). In the USA there are 2.2 million km, 287000 km in Europe (EC, 2011), and 115000 km in Canada (CEPA, 2014). As of 2014, the global network of pipelines is valued at more than 8680 million dollars (MarketsandMarkets, 2014). The volume of hydrocarbons transported daily by pipeline is ever increasing (PGJ, 2011) as they provide the safest means of transport.

Pipelines, including pipes, compressors and pumps, are frequently located in environments which are difficult to monitor and secure (e.g. offshore, remote areas). Attacks or damage to such installations can lead to enormous ecological impact and loss of revenue, potentially leading to international oil market disruptions. Improving oil and gas installation security is a matter of global importance, and the main rationale for the monitoring of oil and gas pipelines is for safety reasons.

Catastrophic events have occurred historically in many countries: a number of accidents happened during the 2000s in Nigeria, where pipelines were frequently vandalised and exploded or leaked causing thousands of fatalities. In 2004, a major natural gas pipeline exploded in Ghislenghien (Belgium), killing 24 people and leaving 122 wounded. In January 2014, one of the TransCanada Corporation gas transmission pipelines exploded and burned, causing a natural gas shortage in Manitoba (Canada) and parts of the USA. In 2010, a large pipeline (> 1m diameter) failed through corrosion and fatigue cracks spilling more than 3000 cubic meters of heavy crude into the Kalmazoo River (Michigan, USA). Hundreds of Michigan residents suffered health effects relating to toxic exposure from the oil, and clean up costs were estimated at 800 million dollars, making this accident the most expensive on-shore spill in U.S. history.

With age, oil and gas pipelines become more prone to corrosion and failure (Figure 1). Furthermore, minor incidents and failures, much more frequent than catastrophic accidents, can cause important environmental damage and economic losses. According to the Energy Resources Conservation Board (ERCB) the number of pipeline breaks per 1000 km in Alberta (Canada) was 1.5 in 2011 and 2012 (ERCB, 2012). In Russia, this rate is estimated to be 110 to 140 per 1000 km per year. In Alberta during 2010 there were 20 crude oil pipeline failures and 241 multi-phase (pipeline carries crude oil and gas) pipeline failures. As the overall infrastructure gets older it requires more frequent revision to prevent incidents that could have a huge impact on the environment, people and economies. Monitoring systems that regularly provide parameters for characterization of the structural and functional conditions of the pipelines, can help to prevent failures, detect problems over time, and undertake maintenance and repair activities.

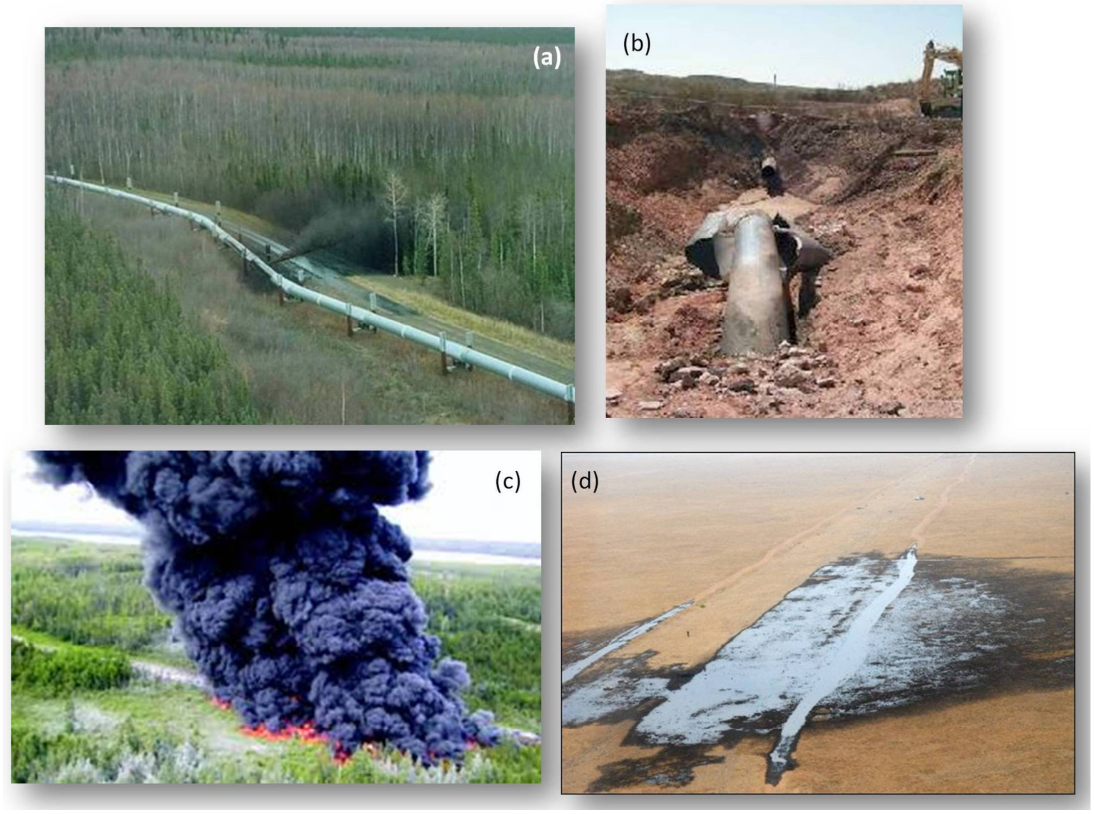


Figure 1. Examples of transportation pipelines failures. (a) Internal corrosion has produced oil leak; (b) Pipeline damaged by external physical aggression; (c) Ruptured pipeline spilling oil that is burnt under control in Cohasset, Minnesota (July 2002) (Photo: US National Transportation Safety Board); (d) A 40-year-old underground 1 m diameter pipeline is fractured producing oil leakage.

2.2 Alternative methods for monitoring oil and pipelines

Currently, the most widely used monitoring methods for oil and gas transmission pipelines are foot patrols along the pipeline route and aerial surveillance using light aircraft or helicopters. Patrols help to prevent placing pipelines, the surroundings, and the security of supplies at risk. However, they have to be carried out at regular intervals throughout the year, and regardless of weather conditions. The economic cost associated with these approaches is therefore also very high.

Progress in high-resolution remote sensing and image processing technology has provided the basis for designing pipeline monitoring systems using remote sensors and context-oriented image processing software (Hausamann et al., nd). Traditional airborne solutions - although beneficial in some ways - bring their own difficulties, in terms of safety and operation: manned aircraft using pilot and/or operator for detection and identification are forced to fly very close to the terrain; frequently can only detect visible effects (i.e. not gas leak detection for instance); and require expensive manned aircraft limiting the frequency and duration of flight. As an alternative, Europe has invested in numerous projects using satellite based remote sensing (e.g. PRESENSE, PIPEMOD and GMOSS) to reach the demands of pipeline monitoring required by pipeline operators. To date, the only conclusion from these projects is that more work is necessary to reach the demands of the pipeline operators.

The use of unmanned aerial vehicles (UAVs), to complement conventional approaches to pipeline supervision, is a new way to efficiently ensure continuity in production. The key to taking advantage of the proliferation of UAV technological innovations lies in determining what business value can be derived from automated data gathering and which tasks can be both electronically and mechanically automated in a workflow. It is also equally important to identify the type of insights that can be obtained from the new data gathered from these environments. These insights can then be used to drive operational decisions or to improve business processes, such as shortening the lead time to problem detection or to ensure productive maintenance of pipelines.

Internationally there is increasing legislation and regulatory pressure to improve the safety and integrity of pipelines carrying hydrocarbons. Oil and gas pipeline monitoring is a specific environmental application of UAV technology, and UAVs are now evolving as highly effective tools for tackling the requirements of pipeline monitoring.

3. UNMANNED AERIAL SYSTEMS (UAS)

Unmanned systems are associated with a host of terms: Unmanned Aerial Systems (UAS), Drones, Remotely Piloted Aircraft (RPA), Unmanned Vehicle Systems (UVS), and Unmanned Airborne or Aerial Vehicles (UAV) reflecting the variety of system configurations and fields of application. Different sources use UAV or UAS as the preferred term. UAV is the term adopted by the UK Civil Aviation Authority (CAA), whilst others suggest that UAS is more correct.

An unmanned aerial vehicle (UAV) is flown without a pilot onboard and is either remotely and fully controlled from another place (e.g. ground, another aircraft, space) or programmed and fully autonomous (ICAO, 2011).

An unmanned aerial vehicle or system comprises the flying *platform*—an aircraft designed to operate without human pilot onboard—, the elements necessary to enable and *control* navigation, including taxiing, take-off and launch, flight and recovery/landing, and the elements to accomplish the mission objectives: *sensors* and equipment for data acquisition and transfer of data—including devices for precise location when necessary.

Aerial and remotely controlled systems for surveillance and the acquisition of Earth surface data have a relatively long history, typically associated with military activities. Photogrammetry and remote sensing technologies identified the potential of UAV/UAS sourced imagery, acquired at low altitudes with high spatial resolution, more than thirty years ago (Colomina and Molina, 2014). However, civilian research on UAVs only began in the 1990s (Skrypietz, 2012). Currently, a profuse emergence of UAV in civilian applications' domains (e.g. agriculture, forestry, mining, marketing, patrolling) has raised awareness of the potential of these aerial systems. A brief description of each of the main elements (platforms, sensors, and auxiliary equipment) now follows:

3.1 Flying platforms

Remotely piloted aircraft or automatic flying platforms can be classified under different schemes, using criteria such as flying height and range, size, and weight (frequently referred to as maximum take-off-weight - MTOW). A strict categorization of UAVs is not however possible because certain characteristics in the various classes overlap (Skrzypietz, 2012). Table 1 provides an overview of the flying platform types as considered by UVS International, a non-profit association dedicated to promote unmanned aerial systems (both manufacturers and operators).

Table 1. Characteristics of non-military Remotely Piloted Aircraft Systems (RPAS)

Name	Acronym	Mass (kg)	Range (km)	Altitude (m)	Endurance (h)
Micro	MAV	< 5	< 10	250	1
Mini	Mini	< 20-150*	< 10	150 *	< 2
Close Range	CR	25-150	10-30	3000	2-4
Short Range	SR	50-250	30-70	3000	3-6
Medium Range	MR	150-500	70-200	5000	6-10
MR Endurance	MRE	500-1500	> 500	8000	10-18
Low Alt. Deep Penetration	LADP	250-2500	>250	50-9000	0.5-1
Low Alt. Long Endurance	LALE	15-25	>500	3000	>24
Medium Alt. Long Endurance	MALE	1000-1500	>500	5/8000	24-48
High Alt. Long Endurance	HALE	2500-5000	>2000	20000	24-48
Stratospheric	Strato	>2500	>2000	>20000	>48
Exo-stratospheric	EXO	TBD	TBD	>30500	TBD

Source: Adapted from UVS international (2008)

Note: *according to national legal restrictions

Note: MAV Micro Air Vehicles; VTOL Vertical Take-Off and Landing; LASE Low Altitude, Short-Endurance; LALE Low Altitude, Long Endurance; MALE Medium Altitude, Long Endurance; HALE High Altitude, Long Endurance

The very small platforms, micro and mini aerial vehicles (Table 1) can fly for less than one hour at an altitude below 250 m. Micro platforms are considerably smaller than mini platforms (i.e. < 5 kg versus 20-150 kg) but both have a similar flying range. An example of micro UAV is the Phantom 1 or 2 (Figure 2), with MTOV below 1.3 kg and a very light payload capacity; Aibot-X6 is another micro UAV with 3.4 kg MTOV and maximum payload of 2 kg. Mini is the most abundant type of platform produced for civilian applications, doubling the number of micro and medium range UAV platforms (UVS, 2014). An example of mini UAV is the Camcopter, with an MTOV of 68 kg and maximum payload capacity of 25 kg (Figure 2). On the other side of the scale, MALE platforms (e.g. Talarion, Predator) and HALE platforms (e.g. Global Hawk, Euro Hawk) have a flying endurance of several days at an altitude of 20000 m. The latter aerial platforms are comparable in size to manned aircraft.

Figure 2. UAV platforms of various types and sizes. Phantom 2 and Aibot-x6 are micro UAV; Camcopter is a mini UAV; Talarion and Predator are MALE UAVs; Global Hawk is a HALE UAV.

Developments of the technology are now providing so-called nanodrones, miniature UAVs able to carry small still and video cameras. These UAVs can fly in all directions and perform manoeuvres and mid-air stunts. For example, the palm-size Micro Drone 2 (Figure 3, a) weights 0.034 kg and has a flying range of 120 m and endurance of 6-8 minutes. Other small drones are now flown as tethered aerial vehicles to circumvent the risks associated with flying. The Pocket Flyer by CyPhy Works (Figure 3, c) is a 0.080 kg tethered platform that can fly continuously for two hours or more, sending back high quality HD video the entire time. With improved tether technology, all data, control and endurance can be built into the tether, providing long endurance. Furthermore, ZANO (Figure 3, b) operates on a virtual tether connected to a smart device, allowing simple gestures to control it.

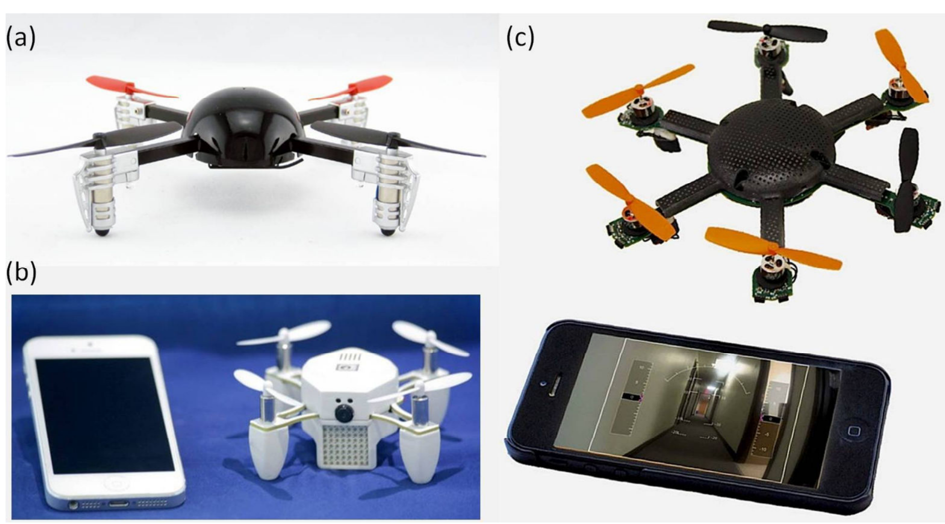


Figure 3. Nano drones in developing phase. (a) Micro Drone 2 quadrotor by Microdrone; (b): Pocket Flyer by CyPhy Works

In the UK, UAVs are usually classified by their size and weight, from small and lightweight (less than 2.7 kg) with a relatively short distance range, up to systems with more than 20000 km range and weight of approximately 12000 kg. To date, only small platforms (< 20 kg) can be used for civilian applications in the UK.

Leaving aside powered blimps and parafoils, as well as non-powered balloon and tethered kites, all small powered UAV platforms based on airframes can be grouped into two main categories: rotary wing UAVs and fixed-wing UAVs. The capacity for Vertical Take-Off and Landing (VTOL) as opposed to Horizontal Take-Off and Landing (HTOL) was a valid criterion for categorizing these two types of UAVs, until some fixed-wing airframes also acquired VTOL capacity.

3.1.1 Fixed-wing UAVs

Fixed-wing UAVs are characterized by a relatively simple structure, making them reasonably stable platforms that are relatively easy to control during autonomous flights. Their efficient aerodynamics enables longer flight duration and higher speeds. This makes fixed-wing UAVs ideal for applications such as aerial survey which require the capture of georeferenced imagery over large areas. On the down side, fixed-wing UAVs need to fly forward continuously and need space to both turn and land. These platforms are also dependent on a launcher (person or mechanical) or a runway to facilitate takeoff and landing, which can have implications on the type of payloads they carry.

Typical lightweight fixed-wing UAVs currently in the commercial arena have a *flying wing* design (Figure 4) with wings spanning between 0.8 and 1.2 m, and a very small fin at both ends of the wing. In-house vehicles tend to have slightly longer wings to enable carrying the required heavier sensors (Petrie, 2013). A second type of design is the *conventional fuselage*. The dimensions are around 1.2 to 1.4 m length for the fuselage and 1.6 to 2.8 m wing length. In the UK there are around 20 companies operating commercial airborne imaging services using fixed-wing UAVs (Petrie, 2013).

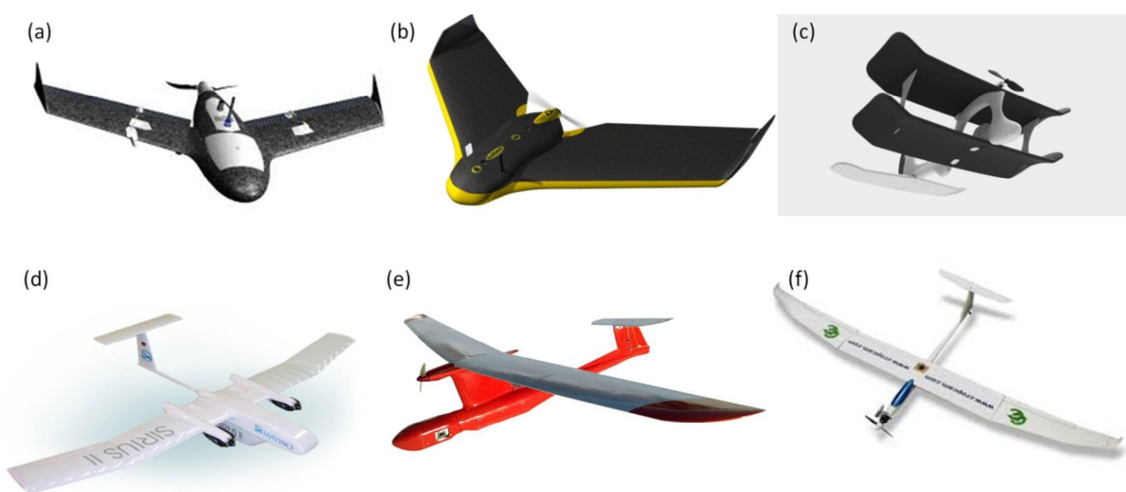


Figure 4. Examples of lightweight fix-wing commercial UAVs. Top row are flying-wing design: (a) Trimble Gatewing X100; (b) swinglet CAM; (c) smartone. Bottom row are conventional fuselage design: (d) MAVinci Sirius; (e) Composites Pteryx; (f) CropCam.

3.1.2 Rotary-wing UAVs

Rotary wing aircraft (N-copter or N-rotor) have complex mechanics, which translates into lower speeds and shorter flight ranges. Among their main strengths, rotary wing UAVs can fly vertically, take-off and land in a very small space, and can hover over a fixed position, and at a given height. This makes rotary wing UAVs well suited for applications that require manoeuvring in tight spaces and the ability to focus on a single target for extended periods (e.g. facility inspections). On the down side rotary wing UAVs can be less stable than fixed-wing counterparts and also more difficult to control during flight.

Single-rotor and coaxial rotor platforms (with two counter-rotating rotors on the same axis) are similar to conventional helicopters, with a single lifting rotor and two or more blades (Figure 5, top row). These platforms maintain directional control by varying blade pitch via a servo-actuated mechanical linkage. Single-rotor and coaxial rotor UAVs are typically radio-controlled and powered by electric motors, although some of the heaviest examples use petrol engines. They require cyclic or collective pitch control.

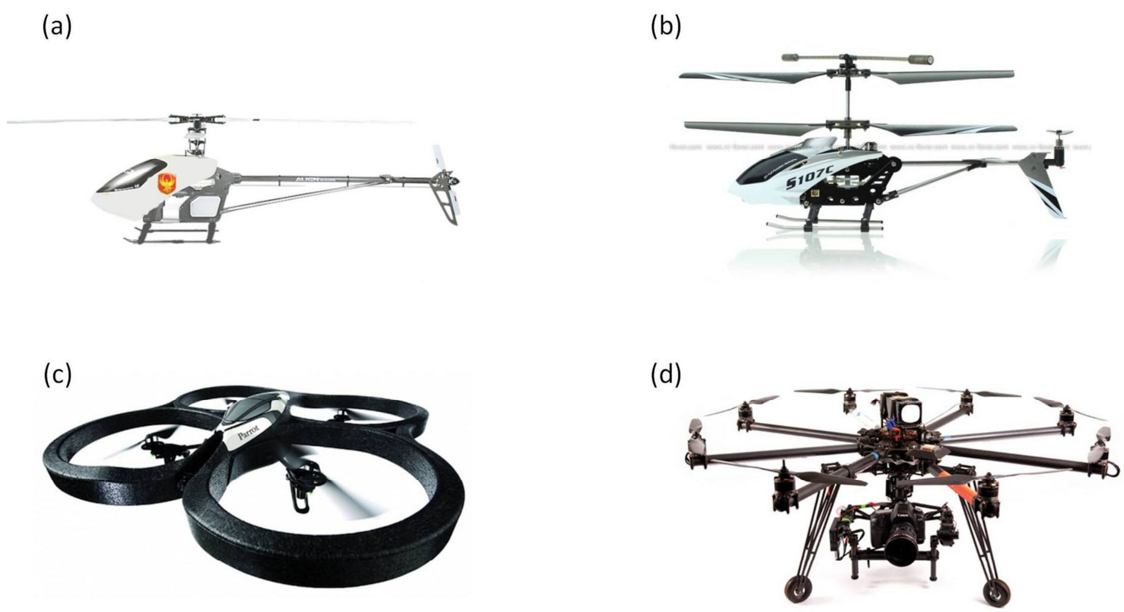


Figure 5. Examples of lightweight rotary-wing commercial UAVs. The top shows single rotor designs: (a) AT-10 (Advanced UAV Technology); (b) Syma S107C . The bottom row shows multi-rotor designs: (c) Parrot AR Drone quadcopter; (d) Cinestar 8 octocopter.

Multi-copters (Figure 5, bottom row) have an even number of rotors and utilize differential thrust management of the independent motor units to provide lift and directional control. As a general rule, the more rotors the higher the payload they can take and are functional in strong wind conditions, as the redundant lift capacity provides for increased safety, and more control in the event of a rotor malfunction or failure. Some platforms now available are capable of autonomous flight, which significantly improves the capability to undertake repeat aerial video and photography.

Rotary-wing UAVs are commonly used to capture oblique aerial photographs and video, and may be used for mapping tasks. Only a small number of commercially available vehicles are equipped with GPS/IMU sub-systems and are capable of autonomous flights covering the ground in a systematic manner so that aerial photography can be used for mapping applications. In the UK, there are now more than 50 companies operating rotary-wing UAVs.

3.2 Sensors

An easy way to classify sensors is to group them into active and passive sensors. Passive sensors measure naturally occurring radiation reflected or emitted by the target objects. Active sensors emit radiation and measure the fraction reflected back by the target objects.

3.2.1 Passive sensors

Passive optical sensors measure radiation in the visible (0.4-0.7 µm) and infrared (0.7-14 µm) part of the electromagnetic spectrum. Optical sensors rely on the sun as the illumination source, which makes them only suitable in daylight conditions, and are limited by atmospheric effects such as clouds, haze, or smoke. An example of a passive sensor not relying on solar radiation is the *passive microwave radiometer* which detects naturally emitted microwave energy of a low intensity. Such an instrument can be used for detecting, identifying and measuring marine oil slicks (Calla et al., 2013).

Optical sensors are similar to the human eye in many aspects. Their operation relies on the principle of measuring the differential amounts of light reflected by different earth or environmental features, normally gathered using specific spectral windows (e.g. blue, green, red). Optical sensors can have a different number of bands with specific band widths. According to the number of bands optical sensors are known as *panchromatic* (a single wide band), *multispectral* (typically 3 to 10 spectral bands) or *hyperspectral* (typically more than 10 and up to hundreds of narrower spectral bands). Colour or panchromatic (B/W) photography can be visually interpreted for the identification of features of interest. There are an increasing number of optical sensors now available for UAVs, ranging from small cameras capable of still photography and video (e.g. GoPro series and iLook cameras), to both small and large DSLR cameras, stereo-cameras, multispectral, and hyperspectral cameras, high resolution cameras on smartphones, or low-cost developments like the HackHD camera (http://www.hackhd.com/).

The range of opportunities provided by optical sensors is constrained by various issues concerning the digital frame cameras that can be deployed on lightweight UAVs. These include: the camera weight relative to the available UAV payload; the very small format of the camera images; the numerous non-metric characteristics of many of the lower-cost cameras; the lenses and resolution; photographic intervals; the need for very short exposure times to help combat the effects of platform instability (i.e. due to speed, roll, pitch and yaw) ; the requirements for high framing rates arising from the speed of the UAV platform over the ground from a very low altitude; and the very large longitudinal and lateral overlaps (i.e. percentage endlap and sidelap) that need to be employed for mapping purposes.

Multispectral

Multispectral imagery is produced by sensors that measure reflected energy within several specific bands of the electromagnetic spectrum. Multispectral sensors usually have between 3 and 10 different band measurements in each pixel of the images they produce. Examples of bands in these sensors typically include visible green, visible red, and near infrared. Simultaneous measurements of multiple spectral wavelengths provide information that can be visually or automatically interpreted. For a given location, algebraic combinations of values in various spectral wave bands such as *vegetation indices* can be very useful to aid in the detection of environmental features.

Multispectral imaging of vegetation is very useful in the identification of plant stress, disease, and nutrient or water status. Pests or other plant stressors such as chemicals (e.g. oil spill) that also leave their spectral mark on a plant, may be easily identified from the air with multispectral (MS) cameras onboard UAVs. As an example, Marcus UAV (a company providing mapping services for precision agriculture), has prototyped a custom payload manifold for the housing of a Tetracam ADC Lite MS camera system. Using infrared camera images collected at specific time intervals, overlapped and aligned, and some spectral filtering software (e.g. Pixel Wrench) NDVI images can be derived. By monitoring differences in NDVI, critical decisions about the plant condition and status can be made early on, something that would be impossible without the aid of remote sensing. Additional advantages of UAV mounted sensors include the ability to fly at a lower altitude, below the cloud base, and with minimal interference in the image record from the atmosphere. UAV platforms can also be cheaper to fly and provide higher spatial resolution imagery for certain applications covering a relatively small spatial extent.

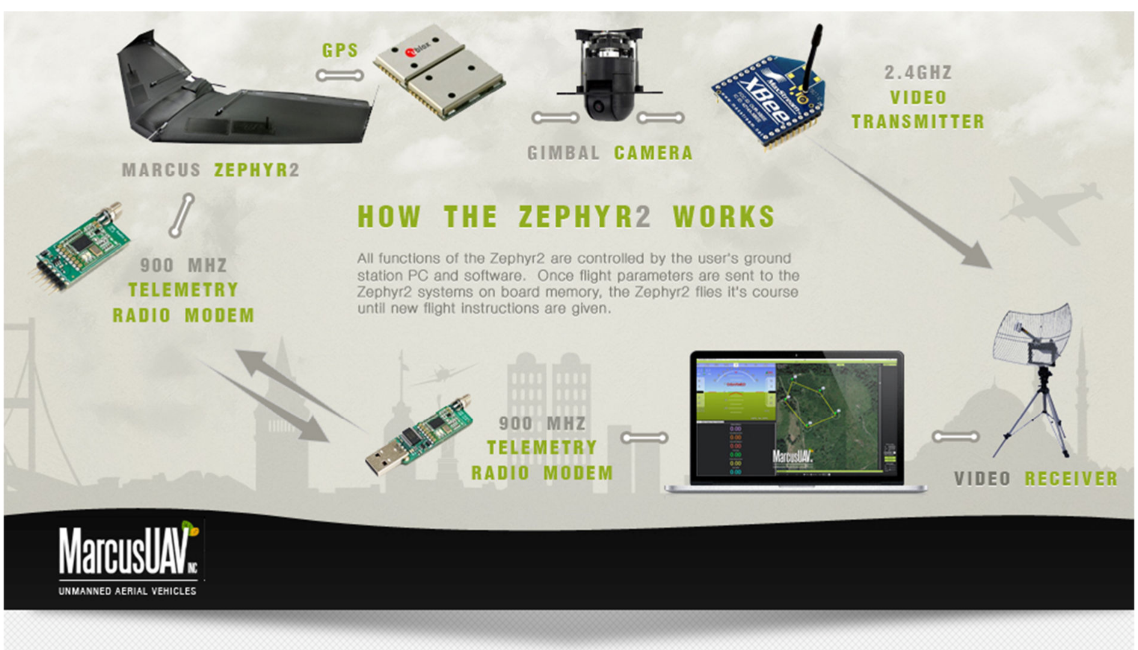


Figure 6. Example of commercial solution (Marcus UAV – www.marcusuav.com) for precision agriculture that incorporates a UAV system for data collection.

Near Infrared (NIR)

Near infrared (NIR) radiation is in the range 0.7-14 µm. The spectral signature of healthy vegetation is very distinctive in the transition between the visible and NIR wavelengths, with absorption of the visible part for photosynthetic activities and high reflection in the NIR. The value of NIR aerial photography for monitoring and mapping vegetation and vegetative status is well documented in the remote sensing literature and has been extended through the derivation of simple vegetation indices (e.g. NDVI, EVI, SAVI), which can be derived if both visible and NIR bands are available, and also using simple filters. Repetitive multi-temporal measurements of the visible and NIR wavelengths of a vegetated area can provide an indication of the health of plants. In the context of oil and gas pipelines this can be very useful to highlight areas affected by the toxicity of oil and gas spills and leaks.

Short wave infrared (SWIR)

Radiation in the shortwave infrared (SWIR) (typically 0.9 to 1.7 µm) is not visible to the human eye but can be sensed by dedicated indium gallium arsenide (InGaAs) sensors. As reflective light, SWIR bounces off of objects and the imagery recorded contains shadows and contrast. Images from an InGaAs camera are comparable to visible images in their resolution and detail, making objects easily recognisable (as opposed to thermal imagery). One of the main benefits of SWIR imaging is its low power consumption, as it uses a thermoelectric cooler or no cooler if the dark current is low enough, while still providing good-enough imagery in low-light conditions. InGaAs sensors can be made extremely sensitive, literally counting individual photons. Thus, when built as focal plane arrays with thousands or millions of tiny sensor pixels, SWIR cameras will work in low light conditions.

Because of their chemical properties many materials have specific reflectance and absorption features in the SWIR bands that allow for their characterization; examples include minerals used in mineral exploration, urban features such as roofing and construction materials, vegetation, and petroleum (e.g. an oil spill). Snow and ice display distinctive variations in some SWIR bands, and SWIR-based imaging can even penetrate some types of smoke, such as from a forest fire.

Only a few commercial companies are making SWIR cameras and even fewer are making the detector material, indium gallium arsenide (InGaAs). Sensors Unlimited and Teledyne Judson are the only two USA developers of SWIR technology, subject to strongly controlled exporting regulations. Xenics in Belgium, Allied Vision Technologies in Germany, and Chungwa in Taiwan are other providers.

Sensors Unlimited - UTC Aerospace Systems - has introduced the smallest SWaP (size weight and power) SWIR camera for unmanned vehicles. The 640 x 512 pixel (25 µm pitch) camera weighs 27 g. The 25.4 x 25.4 x 25.3 mm^3 total volume allows it to easily fit on board most unmanned aerial or ground vehicle systems (UAS or UGS).

Figure 7. The SWIR Nano 640C SWIR Camera, a golf ball and a tennis ball for scale comparison

Hyperspectral

Hyperspectral imaging samples a wide variety of bandwidths in the light spectrum to provide a rich data set and detect objects of interest not visible to single-bandwidth imaging sensors. With a larger number of fine spectral bandwidths, the identification of specific conditions and characteristics are greater. Sensors with hundreds of bands (e.g. 255) are increasingly being used for vegetation species identification and geological characterization, as well as many other applications. Developers of hyperspectral sensors provide flexible and customizable options for the number and resolution of spectral bands in the visible and infrared (e.g. Rikola Ltd). Headwall Photonics, for example, now specializes in hyperspectral imaging sensors that are small and rugged enough to fit on relatively small UAVs. Adding hyperspectral imaging as a standard element in an electro-optical and infrared (EO/IR) sensor suite for UAVs has, however, until recently presented a difficult engineering challenge.

Thermal

Oil and gas leaks have been found to show up well in thermal infrared (TIR) imagery because of the temperature differences between the fluid and the soil. For soils, thermal conductivity is affected by the water content, and conductivity also changes when liquid oil drains into soil. Gas escapes show as cold, whilst an oil leak creates a warm area. Therefore the rationale for detecting hydrocarbon leakages from pipelines using thermal image surveys is based upon differential thermal imaging: comparing images of the same area captured on different days using advanced techniques enables the detection of a change in temperature. However, this has to be set against other factors that can make the soil temperature vary and induce false temperature changes. The theory is that a leak from a pipeline can be detected as a direct consequence of the increase in the heat capacity of the soil together with the oil, relative to that of the soil alone. Regular thermal imaging of the land in the vicinity of a pipeline, just after sunset, should reveal the different thermal properties attributable to the leakage. Specialized computer software is needed to automate the interpretation of the data. The availability of regular imaging data will increase the sensitivity of the data through the use of averaging techniques, to enable small differences in heat capacity of the soil to be detected, on a day-by-day basis. Lightweight thermal cameras have been adapted or specifically developed for use in UAVs.

- The FLIR Quark 640 long-wave infrared (7.5-13.5 µm) thermal sensor was incorporated by Sky-Watch (Denmark) into one of its drones. FLIR Quark 640 is a very small (22 × 22 × 12 mm^3

without lenses) sensor with a flexible configuration of lenses (6 to 35 mm), scene range from -40° to 160°C, and sensitivity of 50 mK. Its weight depends on configuration but is less than 30 g.

- Tamarisk 320 developed by DRS Technology is a long-wave infrared (8-14 μm) thermal sensor of similar size (~30 × 30 × 30 mm^3). It can also be configured with lenses (7-35 mm) and has a scene range from -40° to 67°C and sensitivity of 50 mK. Its weight depends on the configuration, ranging from 30 to 135 g.

Fluorescence

Spectroscopy has also proven to yield reliable results for the early detection of vegetation affected by disease (Garcia Ruiz et al., 2013) and would presumably be equally useful to help detect early effects of oil and/or gas pollution and contamination. Emitted fluorescence is directly linked to primary production and thus measurements of solar-induced fluorescence could be used as an early indicator of the health and status of vegetation. Estimates of fluorescence (F) can be derived from multispectral and hyperspectral radiance sensors, exploiting the Fraunhofer line and decoupling F from the reflected flux. Furthermore, optical indices related to F can be derived from reflectance sensed by multispectral sensors. However, the quantitative estimation of F from the air is complicated by the absorption of the atmosphere en route to the sensor, and approaches to deal with atmospheric effects have yet to be developed (Meroni et al., 2009). The spatial patterns of F provided by imaging spectrometers from the air provide insights into photosynthesis and plant stress, that are different to those provided by spectral indices. For the estimation of F, very high spectral resolution (0.05-0.1 nm) sensors are recommended (Meroni et al., 2009) to allow re-sampling and application of estimation methods, from multispectral to hyperspectral. At present solar induced vegetation fluorescence techniques are less developed than other vegetation monitoring strategies with remote sensing, but it is a promising field being developed.

3.2.2 Active Sensors:

Active sensors emit some kind of radiation and measure the fraction reflected by the target objects as well as the difference in time between emission and reception. Active sensors require power supplied by a source that inevitably adds weight to the aerial system. For this reason active equipment is less versatile for use on UAVs when compared with passive equipment.

Radar

Synthetic Aperture Radar (SAR) is a form of radar using relative motion between an antenna and its target region, to provide distinctive coherent-signal variations. SAR pulses radio waves at wavelengths of 0.002-1 m repeatedly towards a target region. The many echo waveforms received successively at the different antenna positions are coherently detected and stored and then post-processed together to resolve elements in an image of the target region. SAR is used for a wide variety of environmental applications, such as monitoring crop characteristics, forest biomass, ice flows, and oil spills. Oil spills in the ocean or water bodies can be detected using SAR imagery because the oil changes the backscatter characteristics of the water. Like with thermal imagery, differential imaging is necessary for detection of oil leaks. All-weather, night and day capacity for data collection makes radar technology appealing and convenient for surveillance in difficult environments. Radar systems have been integrated in large UAV systems (e.g. military), but there is still a need for small, low-cost, high-resolution radar systems specifically designed for operation on small unmanned aerial vehicles.

- Brigham Young University (BYU) in Utah, USA, has developed some compact, low-cost, low-power SAR systems, including a series of microSAR systems designed for operation on small UAVs. The microSAR design represents a trade-off between coverage and precision versus cost and size. It is an ultra-low-power system (16W) designed for operation on a UAV with ~2 m wingspan. The system records data continuously for over an hour on a pair of compact flash disks then loaded onto a laptop for processing data into images using SAR image formation and auto-focusing software. Image downlink capacity and real-time processing are being developed. The microSAR system consists of a stack of circuit boards (7 × 8.5 × 7 cm^3) and two flat microstrip antennas (0.1 × 0.5 m^2). Minimal enclosures reduce the flight weight to less than 1 kg. Unlike conventional SAR in which short pulses are transmitted and received separated by an interval, microSAR transmission and reception occur simultaneously via continuous-wave linear-frequency modulation, enabling low-power operation. To optimize performance, microSAR uses bi-static operation, in which transmission and receipt occur via different antennas. Designed for operation at 130–800 m height and speeds of 20–50 m/s, microSAR has a swath width of 200–900 m with a nominal one-look spatial resolution of 0.1 × 0.6 m^2, which is multi-look averaged to 1 × 1 m^2 in processed imagery. The averaging reduces the 'speckle noise' inherent in SAR images. The first microSAR operated in the C-band (5.56 GHz), but microSAR systems using other bands have also been built.

- ImSAR (Utah, USA) has developed a NanoSAR series improving from the first NanoSAR-A (0.5 m resolution operating at 500 m height) to NanoSAR-C (0.3 m resolution at 2000 m height). NanoSAR-C weighs less than 1 kg. ImSAR radar has printed circuit board technology in place of the heavy metal tubes that serve as radio wave guides in standard synthetic aperture radars. Etched on fiberglass boards, the radar circuits are similar to the lightweight circuits used in laptop computers and cell phones. NanoSAR-C has a range of 1-16 km and power consumption between 25 and 70W.

LiDAR

Over the last few years, airborne Light Detection and Ranging (LiDAR) surveys have become popular for many applications. Typically LiDAR surveys are carried out using manned aircraft flying at 1500 m or above. At this height they are susceptible to atmospheric conditions and have poor image resolution or a small image footprint. In general, the main constraint to the use of LiDAR on a UAV has been the size and weight of the sensor. UAV imaging systems are generally much lighter than an equivalent LiDAR system. This is due in part to two factors: LiDAR sensors are not nearly as small and light as cameras and a LiDAR system depends entirely upon an accurate inertial navigation system (INS). The imaging system in contrast uses traditional photogrammetry and does not require any INS. Because of this, UAV imaging systems can cover a larger area in less time at less initial expense. Recent commercial developments of LiDAR technology dedicated to UAVs are specified below and also in Appendix 1. Characteristics such as range, flying height, and power consumption are tradeoffs to consider for specific applications and platforms systems:

- Riegl has developed a LiDAR system for UAVs, the VUX-1, beaming 500k shots per second of NIR radiation; it has an estimated accuracy of 10 mm. Its dimensions are 22.7 × 18.0 × 12.5 cm^3 and weights 3.6 kg. The RIEGL VUX-1 is designed to be mounted in any orientation and has a 330° Field of View (FOV). Its maximum range is 900 m.

- Yellowscan has developed a LiDAR sensor for UAVs with 2.2 kg beaming 800k shots per second with multi-echo technology (3 echoes per shot) in the 905 nm wavelength. It has power for 2 hours of autonomy. With a maximum range of 100-150 m depending on conditions and a 100° FOV.

- Velodyne has developed a new HDL-32E LiDAR sensor, with a scanning rate of 700k shots per second. At less than 1.5 kg and smaller than 15 × 9 cm^2, this LiDAR scanner is therefore ideal for UAV applications. Velodyne has also announced a new LiDAR sensor with a scanning rate of 300k shots per second, 0.6 kg of weight and dimensions 10 × 6.5 cm^2. The expected price of this LiDAR sensor is less than 8000 US dollars. Both LiDAR systems work with radiation of 905 nm and have a range of ~100 m.

- Hokuyo has developed a number of small, lightweight LiDAR devices for UAVs, e.g. UTM-30LX. The UTM-30LX is 60 × 60 × 87 mm^3 size and 0.37 kg has a scanning rate of 40k shots per second and a range up to 30 m. Interface to the sensor is through USB 2.0 with an additional synchronous data line to indicate a full sweep. The FOV is 270° and a 12 V power source is required.

To accommodate LiDAR sensors on UAVs, Phoenix Aerial has recently developed the Scout, equipment designed to host Velodyne LiDAR sensors and also a combination of LiDAR and photogrammetric equipment (Figure 8). The Scout has dimensions 12.5 × 22.4 × 18.5 cm and weights 2.5 kg.

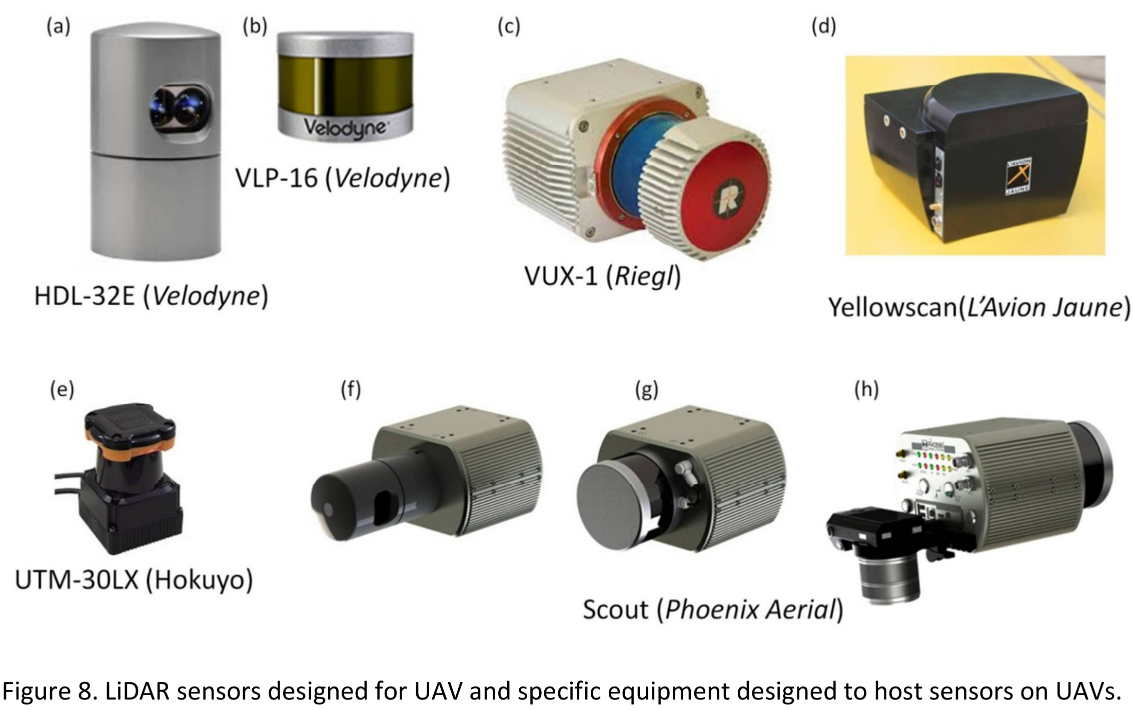


Figure 8. LiDAR sensors designed for UAV and specific equipment designed to host sensors on UAVs.

3.2.3 Video and Still Cameras

The GoPro and competing ultra-compact and lightweight cameras e.g. iLook (Walkera) have proven themselves to professionals and amateurs alike as ideal sensors for recording high resolution digital still photographs and video. With the addition of video downlink hardware and view screens aerial flights can be monitored in real-time (although it is necessary to acquire the help of an additional person to the UAV pilot to monitor the flight using the view screen), and even on smart devices such as the phones and computer tablets. Researchers at Brigham Young University have reported on some of the problems associated with the transmission of video data from small UAVs. While current implementations of UAVs can transmit live video back to the end-user, these implementations have three significant weaknesses: (1) the cost of video communication, (2) redundant video information, and (3) difficulty of information retrieval. Some UAV systems now also take advantage of smartphones and computer tablets instead of traditional screen viewers to monitor the aerial view of the surface.

High resolution imagery (e.g. 12+ Mp) provide detailed colour and filtered imagery from low to medium altitude flights on platforms such as the DJI Phantom 1, Phantom 2 and 3D Robotics IRIS. Using traditional tools and techniques and digital image processing software (e.g. AgiSoft, MosaicMill, 2d3, or Pix4D) the imagery acquired can then be interpreted and analysed manually or on-screen, or information extracted using semi-automated approaches. 3D orthophoto imagery and DTMs can also be generated.

Larger platforms can of course carry larger payloads and even multiple cameras. This means that much better cameras e.g. DSLR can be mounted on a UAV with the end result being much higher resolution digital stills and video which moves the quality of the imagery from the amateur to the professional quality required for commercial applications. In addition, the capability to carry a larger payload means that a better gimbal can be used, as well as numerous other sensors.

3.2.4 Stereo imaging using two cameras

Stereo cameras have been utilised for a number of roles on UAVs. Firstly for capturing stereo-imagery: taking two photographs simultaneously from two slightly different viewpoints provides a basis for generating 3D imagery or views. Cameras such as the Fuji Finepix Stereo camera have been successfully mounted on small N-copters for this purpose (Haubeck and Prinz, 2013). Secondly, stereo-cameras can be used as the basis for UAV navigation systems. Stereo imagery can be used to work out the distances to any obstacles, such as any planes, buildings, or mountains ahead; detect the nearest object in the field of view, to enable a warning to be issued, if the UAV is about to collide with the obstacle; enable the UAV to use the distance-to-obstacle feature, to calculate a flight path, to avoid the obstacle. Stereo imaging can be accomplished through the use of two imaging CCD cameras and suitable software, such as the Stanford Research Institute (SRI) Small Vision System software. One image can be fitted with a vertical polariser, the other with a horizontal polariser. The difference between the images from the two imagers can be used to detect the presence of water, since only light with a horizontal polarization is reflected from a water surface.

3.2.5 UAV Sensor and Technology Developments

Currently some practical and operational limitations limit developments in UAV capability. The most important is probably the weight of higher resolution sensors in relation to the payload capacity. This is particularly relevant for the smaller platforms since electro-optical infrared sensors are generally 10-30% of payload weight and less than 5% the vehicle weight. Other constraints are related to camera optics and aperture, survivability, and data recording. Newer cameras can produce more data, but do also have more electronics that require more power and produce more heat. Gimbals and payload compartments are also increasingly thermally challenged. Although many applications using small UAV platforms make use of standard off-the-shelf technology, increasing demand for better imaging systems might result in UAVs with a larger payload capability. As an alternative, recent technological developments encourage high expectations on the miniaturization of sensors and on higher power capacity of batteries.

UAV sensor designers are now pushing into uncharted technological territory as they increasingly consider extreme design tradeoffs to improve sensor performance whilst also attempting to reduce size, weight, and power consumption. Not only is there a demand for ever-smaller, lighter, and less expensive electro-optical payloads, but demand for capability is also increasing. As electro-optical and electronic component technology becomes smaller, lighter, and more affordable, so payload designers sometimes have the option of choosing between smaller size and weight, or more capability. Sometimes they strive to do both, and this will present some interesting possibilities in design tradeoffs.

Today, the UAV platform is setting the agenda for unmanned electro-optical sensor payloads. At the top of that UAV agenda is a broad trend towards growing numbers of relatively small UAVs that can provide local-area and short-duration surveillance. Size and weight are crucial, because for these small UAVs one gram of payload weight can translate into 10 minutes worth of power to operate. Many UAV systems that are suited to specialised applications are therefore increasingly custom-designed.

An obvious approach to addressing the size-and-weight problem is to combine several different electro-optical sensors into one integrated payload. Some of today's electro-optical payloads combine a daylight video camera, laser rangefinder, and one or more kinds of infrared or multispectral imaging sensors. As an example HoodTech (www.hoodtech.com) has been able to combine midwave IR sensor, daylight video camera, and laser rangefinder into a single payload that weighs about 1.2 kg.

One of the most crucial, yet largely ignored requirements for electro-optical payloads in small UAVs is the ability to keep the sensor stable enough whilst in flight to provide usable video and images. The smaller the UAV, the more influence any gust of wind can have on the sensor's ability to focus on areas of interest. Historically, stabilization technology has been a problem to address – the solutions being heavy, expensive, and power-demanding. Yet, despite perceived drawbacks for use on small UAVs, sensor payload designers are focusing on the use of stabilization technology, not only to improve performance, but also to address size and weight.

Payload engineers are faced with highly technical demands, like delivering very narrow field-of-view images, on-board image processing, video compression, multi-spectral simultaneous imaging, and other technically advanced attributes that become ever more challenging from small platforms buffeted in the wind. Furthermore, they are always faced with limited “budgets” in terms of mass, volume and power for small UAVs (Johnson, 2012).

3.3 Auxiliary equipment

Aircraft and the onboard payload equipment are also supported by a series of elements and systems, necessary to make an UAV mission successful. Some of the auxiliary technologies that may support UAV’s missions are listed below.

3.3.1 Position and navigation systems

The position of an unmanned aircraft has to be known and controlled at all times, be it by the remote operator, or by the autonomous pre-programmed flight plan. The quality of lightweight and compact GNSS equipment now available provides for the acquisition of high accuracy location information (especially when operated as DGPS) and facilitates all UAV navigation. For remote control, in cases were non-autonomous operations are necessary, other solutions are required. The most common systems are:

Radar tracking: a transponder is fitted to the aircraft that responds to a radar scanner emitting from the control system (CS). The aircraft position is seen on the radar display of the CS in bearing and range.

Radio tracking: the radio signal carrying data from the aircraft to the CS is tracked in bearing from the CS whilst the range is determined from the time taken for a coded signal to travel between the aircraft and the CS.

3.3.2 Autonomous Flight

Whilst many small UAV can be described as semi-autonomous e.g. DJI Phantom 1, increasingly there is a demand for autonomous systems for the larger n-copter and fixed-wing UAVs to provide, amongst other things, the means to fly larger and more remote survey areas, and also to ensure repeated overflights covering the same survey area providing coincident imagery and video.

Autonomous flight capability is well developed for the larger and more sophisticated drone platforms and covers the ability of the platform to navigate amongst other things obstacles in the flight path. This is clearly advantageous for systems that may be expected to fly in enclosed spaces.

In this document, however, the capability for autonomous flight is considered to be that which allows the platform to both take off and land automatically, as well as fly the aerial ‘sortie’ along a pre-defined flight path with n-waypoints that have been pre-programmed by the UAV operator. Where a survey is likely to be repeated at certain time intervals the autonomous capability is clearly essential to ensure that the repeat imagery covers exactly the same area.

An example of small and affordable autonomous UAV platform is the ArduCopter, which caters for both RC flight and autonomous flight. Arducopter makes use of the APM 2.x autopilot and the *Mission Planner* (MP) software flight system. This low-cost system is frequently cited for use with other UAV platforms and can be easily programmed and monitored with the aid of a smartphone or tablet. Other software examples for planning and controlling autonomous UAV flights are *APM Planner*, *Droid Planner*.

Figure 9. Screen Interface for Mission Planner (left) and Droid Planner (right).

3.3.3 Communication System (CS)

For communication between a UAV and the CS the transmission medium is usually radio frequency. The complexity, weight and cost of the radio equipment are determined by the range of operation possible, the sophistication of the payload transmission, and the need for security. Light - in the form of a laser beam or via optical fibres are some alternatives. The uplink information (i.e. CS to aircraft) normally consists of: a flight plan, real time flight-control commands, control commands to the different payloads, and updated positional information. The downlink (i.e. aircraft to CS) information consists of the payload data (e.g. imagery), positional data, and aircraft housekeeping data (e.g. battery state or fuel state).

3.3.4 Launch, recovery and retrieval equipment

Launch and recovery are relatively easy for the rotary wing platforms with the capacity for vertical flight. On the other hand, fixed-winged vehicles require additional equipment to assist with these operations. These include:

Launch equipment is frequently a ramp along which the aircraft is accelerated on a trolley until it reaches enough airspeed to sustain airborne flight. The acceleration is provided by compressed air or by rocket. The size and desired speed of the UAV determines the adequacy of launchers (see Figure 10).

Recovery equipment can be a parachute installed within the aircraft to be deployed at a suitable altitude over the landing zone. A means to absorb the impact energy is also needed, like an airbag or piece of material easily replaceable.

Retrieval equipment. If the UAV is heavy and non man-portable, a means to transport it to the launcher is necessary.

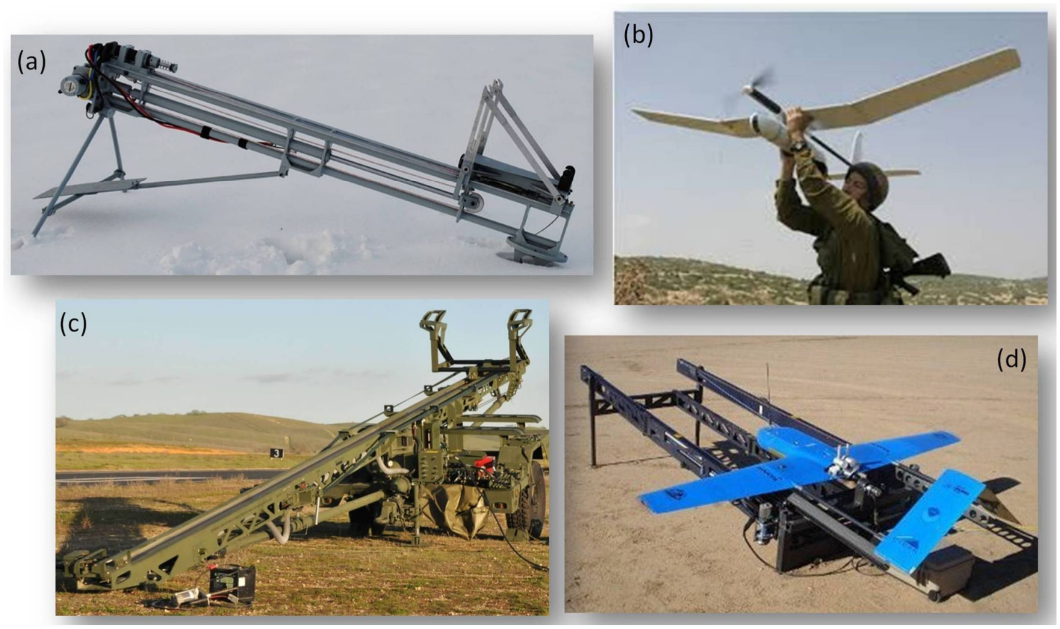


Figure 10. Examples of UAV launching systems. (a) Minilauncher for 6-30 kg UAVs; (b) Manual launch; (c) Heavy launcher for large UAVs; (d) “Universal” UAV launcher, adaptable to various platform sizes.

3.3.5 Mechanics

An important requirement for most UAV acquiring data, still imagery or video, oblique or vertical, is the ability to control the direction in which the sensor is pointing during the flight and to ensure that the sensor maintains the same orientation at all times. Properly securing the sensor on the front or underside of the UAV platform is crucial, because rotor vibration and gust instabilities very easily translate into blurred images and shaky videos, particularly with N-copters. Simple solutions for stabilization include damping the sensor (e.g. camera) with a mounting bracket and rubber mounts in between the UAV and the sensor; this will help reducing or eliminating what is known as the ‘jello’ effect on video imagery. But more specific mechanics adapted to both the platform and sensors might be necessary. An elaborate solution is the addition of a *gimbal,* a precision-engineered component that provides control of pan, tilt (Hausmann et al., nd) and even yaw—in case of 3D gimbals. For each combination of sensor and platform a specific gimbal (Figure 11) is required.

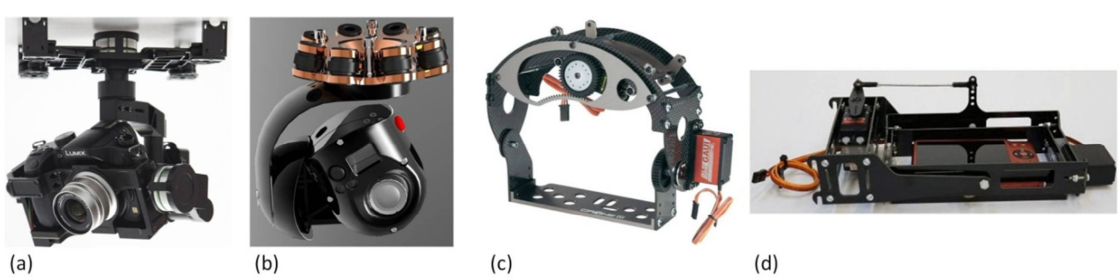
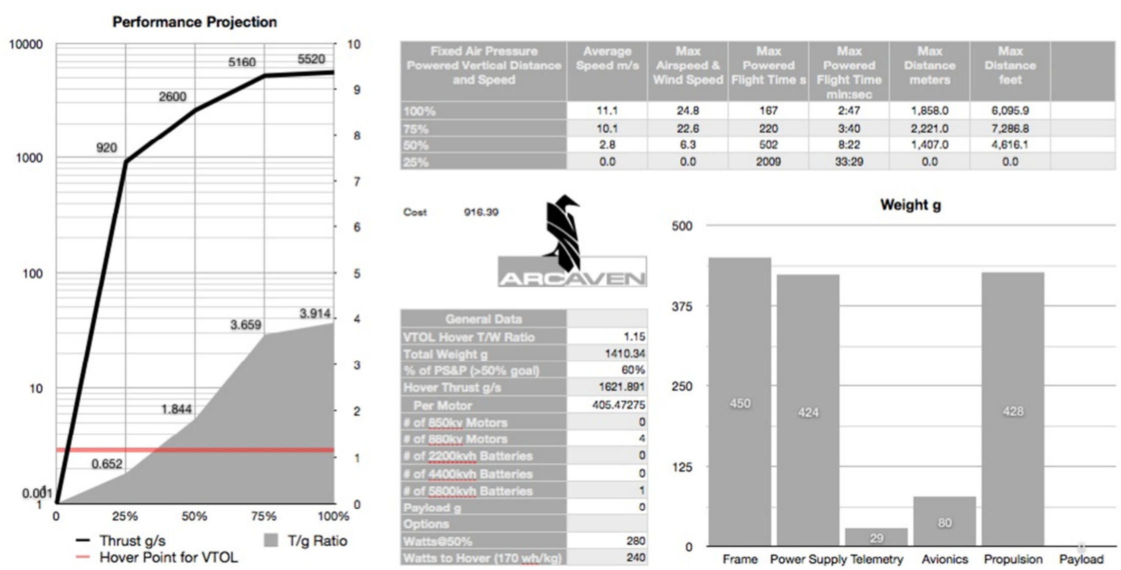


Figure 11. Examples of specialized gimbals. (a) DJI Zenmuse Z15-GH3 3-axis; (b) 3 Axis Gopro Hero 3; (c) Gaui Crane III; (d) Flatmat 2 axis.

3.3.6 Payloads

Some UAV manufacturers (e.g. DJI) do not publish a payload specification, but they do suggest that the total weight of platform and payload be less than certain quantity, e.g. 1000 grams. For the basic DJI Phantom the effective payload is approximately 200 grams with a range of about 300 meters, both of which can be extended with modifications. Many of the DJI platforms, such as the Phantom (1 and 2) are therefore designed to carry only a sensor such as a GoPro 2, 3 or 4 (only without the plastic waterproof case and gimbal assembly) which can easily be lifted by this quadrotor. The same applies to Sony's new action-cam and many other lightweight sports and other cameras e.g. Walkera's iLook which are all similar in size and weight to the GoPro camera.

The maximum payload a UAV can cope with is highly dependent on structural components and battery power. A concept typically used for comparison is the *lift efficiency*, the relation of UAV structure weight over payload weight. Recommended values for payloads are empirical and dependent on a number of factors



Fixed Air Pressure Powered Vertical Distance and Speed	Average Speed m/s	Max Airspeed & Wind Speed	Max Powered Flight Time s	Max Powered Flight Time min:sec	Max Distance meters	Max Distance feet	
100%	11.1	24.8	167	2:47	1,858.0	6,095.9	
75%	10.1	22.6	220	3:40	2,221.0	7,286.8	
50%	2.8	6.3	502	8:22	1,407.0	4,616.1	
25%	0.0	0.0	2009	33:29	0.0	0.0	

General Data	
VTOL Hover T/W Ratio	1.15
Total Weight g	1410.34
% of PS&P (>50% goal)	60%
Hover Thrust g/s	1621.891
Per Motor	405.47275
# of 850kv Motors	0
# of 880kv Motors	4
# of 2200kvh Batteries	0
# of 4400kvh Batteries	0
# of 5800kvh Batteries	1
Payload g	0
Options	
Watts@50%	280
Watts to Hover (170 wh/kg)	240

Figure 12. Graphical example of payload characteristics for a UAVs

3.4 Regulations

With the rapid development of UAV applications worldwide, coupled with a fair number of ongoing incidents and accidents concerning UAVs and other airborne platforms – usually highlighted by the media - there is a growing call worldwide for tightening-up the current rules and regulations concerning who, what, where and when UAV platforms can actually be flown. Already in many countries (e.g. the UK, USA, Australia and Canada) there are moves to regulate UAV flights, and to necessitate education and training of operators and pilots, including best practice, guidelines, and operator insurance amongst many other things. Whilst the UK and USA have been relatively slow in addressing this rapid growth in platform and user-base, Canada is frequently cited as moving in the right direction concerning the rapid proliferation of a wide range of UAV technology, from the hobbyist to the commercial service provider.

In 2007, a group of national authorities under the leadership of The Netherlands joined in an effort to develop harmonized operational and technical regulations for "light" (i.e. less than 150 kg) UAS. JARUS (Joint Authorities for Rulemaking on Unmanned Systems) is open to participation from all civil aviation authorities and current participants are from European and non-European countries. JARUS is organized in seven working groups focusing on diverse guidance and regulatory aspects (e.g. detect and avoid technology, command control and communication). The primary output will be recommended operational requirements and certification specifications. For example, the group dealing with technical requirements of platforms is focusing on establishing certification specifications for various types of aircraft, starting with light unmanned rotorcrafts.

Expansion of UAVs and applications will have an impact on the airspace, but other industry areas will also be affected and need regulations and adaptation. UAV communication with the ground control system (GCS) requires radio frequencies with sufficient band width. The International Telecommunication Union (ITU) has not yet allocated such bandwidth to UAVs, hence they may have to use different radio frequencies in every country (Everaerts, 2008), something to be considered by international operators and manufacturers.

As it is not the purpose of this report to cover in detail all the current worldwide regulations – simply to include information and raise awareness in relation to the longer-term use of a range of UAV platforms in the context of oil and gas pipeline monitoring – further details can be found elsewhere (e.g. Colomina et al. 2014; van Blyenburgh 2014). However, the EU regulations will be covered briefly as the report primarily focuses on UAV applications in the UK.

3.4.1 EU Regulations

The capacity and responsibility to regulate UAVs rely on different bodies internationally. In Europe the European Aviation Safety Agency (EASA) regulates all aspects in relation to UAV that have a Maximum Take Off Mass (MTOM) of over 150 kg, while national Civil Aviation Authorities (CCA) deal with light systems of MTOM less than 150 kg (including fuel) which should fly at altitudes below 150 m.

Legal operations with UAVs in Europe currently require:

The RPAS (RPA and remote pilot station) to be certificated or approved by the National Aviation Authority (NAA) of the country where the operation takes place, or certificated or approved by a Regional Authority (RA) with delegated authority. This certification should cover all system constituents necessary for command and control (e.g. transceivers) installed on board the RPA/UAV or on the ground, and under direct management of the Operator.

- The Command & Control link to be provided by a Communications Service Provider (COM SP) has to be certificated or approved by the NAA or a RA of the country where the operation takes place;
- The Remote Pilot (RP) has to be licensed by the NAA of the country where the operation takes place;
- The *Operator* has to be certificated, approved, or authorized by the NAA of the country where the operation takes place, and is required to possess the obligatory third party liability insurance (which may vary in function of the type of operation).

For a specific aerial operation, *approved operators* have to apply for a *flight authorization* using a specific RPAS in a defined area, possibly on specific day(s). The duration of the validity of the flight authorizations varies from one day to two years in different EU countries.

The International Civil Aviation Organization (ICAO) aims to provide fundamental international regulatory framework through standards and recommended practices with supporting Procedures for Air Navigation Services (PANS) and guidance material, to underpin routine operation of UAS throughout the world in a safe, harmonized in a seamless manner comparable to that of manned operations. According to ICAO, only Remotely Piloted Aircraft (RPA) will be able to integrate into the international civil aviation system in the foreseeable future.

RPA that utilize visual line of sight (VLOS) as the basis for navigation would not require an on-board means for determining position or the ability to fly an instrument approach. Operations of these aircraft are usually conducted under visual meteorological conditions (VMC) to ensure the remote pilot can maintain continuous and direct visual observation of the RPA and its surrounding environment. In cases where small RPA have a requirement to fly beyond VLOS, they will need a means to meet navigation capabilities for the airspace within which they are operating. This could involve an alternative means of achieving the navigation performance. RPA that traverse several airspace volumes may operate for the most part under Instrument Flight Rules) (IFR). Such RPA will have to meet the communications, navigation, and surveillance requirements and have an appropriate aircraft operational certification associated with the airspace.

3.4.2 UK Regulations

The Civil Aviation Authority (CAA) in the UK has regulated UAS flights in two documents which are eventually updated to incorporate relevant changes: CAP393 *Air Navigation: The Order and the Regulations* (CAA, 2014), and CAP 722 *Unmanned Aircraft System Operations in UK Airspace* (CAA, 2012). Small Unmanned Aircraft (lightweight UAVs of less than 20kg) are exempted from the majority of the UK Air Navigation Order (CAP393 document). However, detailed regulation is established specifically for these vehicles in articles 166 and 167 of the CAP393.

UAV that weigh **more than 20kg** are currently banned from flying in civilian airspace other than in a large zone in west Wales and a smaller one over the military base at Boscombe Down.

UAVs that are **less than 20kg** (small unmanned aircraft) can fly in normal airspace for private use as long as the operator is not planning to use data or images from the flight acquired by flying close to people or objects. UAVs have to remain 150m from congested events or large assemblies, 50m from a person or building, and within visual line of sight (VLOS) (500m horizontally and 122m vertically). Flights beyond VLOS can be permitted but the operators need to demonstrate they can fly the plane safely. Live-streaming from the UAV to the pilot is not considered a good enough measure by the CAA to allow drones to be flown beyond VLOS. Anyone who is using a drone under 20kg for commercial purposes has to be licensed to ensure that they are sufficiently trained to fly the plane and have the appropriate insurance in place.

General guidelines to fly UAV for civilian applications in UK:

- Small UAV under **7kg** can be flown exempt from any restrictive rules
- UAV under **20kg** can be flown following CAA rules
- Fly inside visual line of sight (**VLOS**):

  a) Vertically < 400ft (~122m)

  b) Horizontally < 500m

- Maintain a **pilot in control**, (ability to take manual control and fly the aircraft out of danger)
- Stay away from built-up or congested areas
- A permission from the CAA is required to:

  a) fly for commercial use industry

  b) fly near congested areas

Currently there are two companies qualified to assess pilot competence for SUA on behalf of the UK CAA. EuroUSC (European Unmanned Systems Centre) is authorized by the CAA to asses the airworthiness of lightweight UAS of 150kg and under, and provides the Basic National UAS Certificate (BNUC) for lightweight UAS pilots and crews. Of special interest for UAS-based photogrammetry and remote sensing is the BNUC-S, for the operation of SUA (with a Maximum Take Off Mass (MTOM) of less than 20 kg) that are used for “aerial work” under Visual Line of Sight (VLOS) or Extended VLOS (EVLOS) operational conditions. A second company assessing pilot competence for SUA flights is Resource UAS. Resource UAS assessment is called RPQ-S (Remote Pilot Qualification-Small). Both certifying organisations also offer a service to help people in the process of obtaining flying permissions. The list of CAA-approved commercial operators of Small Unmanned Aircraft (not exceeding 20 kg) is updated approximately every three months. From the 21st October 2014 there were 359 operators registered in the UK.

Currently, as of December 2014, with the rapidly growing interest in and expanding end-user community, there is increasingly growing concern about the use of UAVs of any size in general. Daily reports of accidents and near misses between drones and civilian aircraft has escalated concern about the safety issues of these small aerial platforms, not so much for commercial operators, but the growing number of individuals and hobbyists who clearly have no sense of the danger and risk that carelessly flown UAV platforms – no matter how small – can pose to people, animals, installations, and now passenger airliners, aside from the security and privacy issues that have been raised. Irrespective of whether or not these platforms are classed as toys or aircraft, all platforms – with or without sensors on board – can pose considerable risk which ultimately will probably lead to a requirement for not only extended guidelines for their safe and responsible operation, but also training, retraining, and insurance.

4. USE OF UAVS FOR OIL AND GAS PIPELINE MONITORING

UAVs are expected to play an important role in the inspection, monitoring, and maintenance of oil and gas pipelines. Unmanned vehicles are likely to do anything the energy companies don't want to send people to do (e.g. dangerous operations). Small aerial platforms are also promising for enhancing safety (e.g. rescue missions) and environmental protection (e.g. monitoring wildlife).

4.1 Current use of UAVs for oil and gas pipeline monitoring

Oil and gas companies are looking into incorporating UAVs as part of their *Intelligent Pipeline Management* initiatives. A number of feasibility studies have taken place, but only a few examples are already in an operational phase. Some examples of current pipeline monitoring systems - illustrating different scenarios - are summarized below in the Case studies; note that there is a different monitoring goal in each case, with a corresponding appropriate strategy and related combination of platform and sensor.

Case 1: BRITISH PETROLEUM AND AEROVIRONMENT
Goal: Inspection of the oil field area for detection of deteriorated infrastructure and areas vulnerable to flood. **Platform**: Puma AE (hand launched, battery powered) **Sensor**: LiDAR or EO/IR **Technique**: Production of 3D maps of the Prudhoe Bay oil field roads, pipelines and well pads. **Comments**: This is the first (accomplished June 2014) large-scale, government-approved commercial use of unmanned aircraft in the U.S. AeroVironment's UAS operators perform photogrammetric and LiDAR analysis to survey and monitor Prudhoe Bay infrastructure, including the gravel roads, pipelines and a gravel pit. The Puma AE's ability to fly low (i.e. 120 - 150 m above ground level), and slowly (< 40 knots), provides BP with highly accurate location maps to help manage the complex. The Puma AE has a wingspan of 3 m, 6 kg weight, and it is capable of up to 3.5 hours flight time per battery

Case 2: CONOCOPHILLIPS AND BOEING
Goal: Surveying marine mammals and ice areas in the Arctic, necessary to meet environmental and safety rules before drilling on the sea floor **Platform**: Scan Eagle X200 (hand launched, ~18 kg and 3.1 m wingspan) **Sensor**: EO/IR imagers and video **Technique**: Offshore surveys taking off from a vessel. Controlled by a pilot on the Westward Wind, the ScanEagle sends real-time video and telemetry to the ground control system on the vessel

Comment: On September 24 2014, ConocoPhillips announced it had completed the country's first commercial UAV flight off of Northwest Alaska in the Chuckchi Sea. The ScanEagle UAV was launched from Fairweather's Westward Wind research vessel during a week of flights.

The Puma AE and ScanEagle X200 are the first two UAVs approved by the US FAA for commercial applications. They both were given a Restricted Category type certificate, enabling operation in certain sectors of the Arctic area, at a maximum altitude of 600 m, 24 hours a day for research and commercial purposes. This certification represents a precursor of open UAV commercial operations expected to be approved by US Congress in 2015.

Case 3: AERONAUTICS
Goals: 1. Patrolling offshore fields for security 2. Undertaking leak detection in buried oil and water pipelines **Platform**: Aerostar **Sensor**: IR camera **Technique**: Differential thermal imaging, Ultra Wideband, or differential RF, sub-surface probing. Ultra Wide Bandwidth (UWB) ground probing Radar is used to spot oil leaks, detect buried metallic objects for some of the longer oil and gas pipelines. **Comment:** Aerostar has a 12 hour flight endurance and slow loitering speed. The flight path is fully programmable making it ideal for surveillance. Aerostar can remain in the air the whole night long and inspect each rig thoroughly.

Case 4: BRITISH PETROLEUM AND UNIVERSITY OF ALASKA FAIRBANKS
Goal: Pipeline inspection for potential leak detection in Alaska and change detection. **Platform**: Aeryon Scout **Sensor**: High resolution visual and IR cameras **Technique**: Observation from near ground level, with top and side pipeline flights. Detection of hotspots with thermal images allowing closer inspection; change detection through repetitive flights. **Comment**:

With the spread of technologies, new possibilities for pipeline monitoring systems are emerging, for example the utilization of a UAV equipped with *lead detection sensors*. Also, UAVs carrying high spatial resolution sensors greatly enhance the security of oil transfer, if compared to static sensors. Static sensors are typically able to detect leakage at a specific target place and are unable to track the damage. In contrast a UAV mounted sensor can acquire high resolution pictures from the required angles and can easily be reassigned to perform another monitoring task.

To date, many of the oil and gas monitoring systems in use, or under development, are based on large UAV platforms, carrying sophisticated sensors, and flying at altitudes that permit repeat coverage of large areas. These are very costly and sophisticated drone-based systems, frequently surveying areas in conflict to assure security. However, it is worth remembering that UAV technology has recently been dramatically altered to provide small scale – micro-UAV – platforms and sensors that have potential for monitoring pipelines at the more local scale. It is in this particular area of development that progress is now very rapid. For example, Steadicopter's rotary UAV-based products can monitor and inspect oil and gas pipelines by flying and hovering at a low altitude using special camera sensors. The film footage is sent in real time to the ground operator for editing and to enable the assessment of the pipeline's condition.

4.2 Detection of hydrocarbon leaks from pipelines

Oil and gas leaks can be detected by a difference in temperature, and a change in vegetation vigour or water colour by difference of IR images. IR imaging can be extremely helpful for surveying oil spills, making it easier to identify where the oil is spreading. IR imaging capabilities enable the UAV to detect leaks that would otherwise not be visible, providing critical information that increases the situational awareness of first responders to the incident, and increasing safety and the ability to make better decisions in the clean-up planning efforts. Likewise, specialized sensors can also be used to detect emissions from gas leaks. There is therefore a critical role for the UAV in the IR inspection of the thousands of miles of pipelines that transport oil and gas around the world. Undetected leaks have frequently caused disastrous fires, explosions and loss of life, as well as heavy economic losses. UAVs are the best and most economical type of platform for this inspection work.

Autonomously guided UAVs flying along the pipeline just after sunset, with an on-board thermal imaging camera to map the ground temperature is a cost and energy effective way by which this task could be routinely performed with minimal atmospheric pollution. Experience reveals that a survey can be carried out at a low flight altitude (up to 100 m) with image resolution of 0.1 - 0.2 m. Images can clearly show pipeline thermal traces, watered sites with high danger of corrosion, and hydrant stoppers. Leakage points look remarkably different to the surroundings; they have a high contrast and are very cool, due to adiabatic gas extension in gas lines or are warmer than the environment in oil pipelines. Sites of oil spills are therefore easily identified. It has been estimated (Barnard Microsystems, 2014) that the TAM 5 UAV would use only 1.33 kg of fuel to fly the almost 1800 km of the Baku-Tbilisi-Ceyhan (BTC) pipeline with 16 planes starting from each pumping station; no pilots are needed and the takeoff and landing can be automated, as well as the data analysis, which could be done anywhere in the world. A small UAV fitted with an IR camera can cost about $85000, while it costs $3000 to send a helicopter to monitor an oil pipeline for an hour; drones would therefore, pay for themselves within 29 hours (Kroetsch, 2013).

Thermal properties of the soil around the pipeline vary not only with the presence of hydrocarbon (leakage) but also with rainfall and vegetation condition. To overcome derived limitations of the approach based on repetitive IR images for detection of oil spills advanced image processing and interpretation techniques, as well as supporting methods (e.g. impedance measurements) would be convenient.

4.3 Advantages and limitations of UAVs for monitoring pipelines

Among the advantages of UAVs over other airborne platforms for monitoring tasks (Table 2), the cost, operational safety and freedom of use are important factors. Ground surveys are much more expensive, and aerial surveys are also less secure and flexible. Other important benefits of UAVs are related with weather conditions. Surveys based on conventional aerial platforms are restricted by wind, clouds, and other climatological agents, while UAVs are very flexible benefiting from below cloud flying altitude and short term change of plan. The low height flight provides for high spatial resolution images. UAVs can also make observations in difficult environments where traditional aircraft cannot access. The cost per hour of UAVs can be as little as $3.0, making the return on investment very favourable (EmacoGroup, nd). Since there are no crew members on board, the vehicle safety concerns are alleviated and insurance costs are reduced, further improving the benefits of this approach.

In comparison to small UAVs – which typically operate at less than 125 m – traditional airborne platforms have some disadvantages for certain applications. There is a wide range of geospatial and geophysical sensing and imaging technology that can now potentially be mounted onto UAVs but its use will depend on the platform. Data gathering means include, but are not limited to GPS and inertial navigation systems (INS), high-resolution digital cameras, infrared and thermal imaging cameras, hyper-spectral imaging systems, LiDAR, Cesium or Potassium magnetometers for magnetic mapping, Quantum cascade lasers for ethane detection, miniature synthetic-aperture radar (SAR) and others. In addition, because drones can fly in temperatures of -33 C and in 50km/h winds, they offer a safe alternative to manned flights in storms and arctic climates.

Table 2. Main advantages and disadvantages of using UAVs for monitoring oil & gas pipelines

Advantages	**Limitations**
Safety in operations. Operational risk is reduced	Legal constraints: • lack of regulation • restriction of use in certain areas • restricted size for free flight
High temporal and spatial resolution data	Specialist expertise required
Programmatic flexibility: • use when convenient (weather) • on-the-fly change of schedule	Small scale of operation: • only small platforms permitted for civil use • limitation to carry specialized sensors due to weight
Access to difficult areas and perspectives	
Economic cost: • inexpensive insurance • reduced human expenses	Lack of standards
Environmentally friendly: less noise, emissions, pollution, and disturbance	Lack of collision avoidance technology
Imagery of very high spatial resolution	

Currently the greatest limitation for general use of UAVs lies in the absence of legislation and regulations to operate in airspace which is non-segregated from manned aircrafts airspace (Skrzypietz, 2012). Concerns supporting this restriction are related to security, based on a UAV’s lack of on-board capability to sense and avoid other aircraft. There are also claims of the need for specific air traffic management procedures. Furthermore, certain regulations exist about flying the UAVs in specific localities and at certain heights – within distances of e.g. airports, line of sight, and there is a requirement of some sort of certification and insurance for commercially-based flights. European countries are planning, in close cooperation with aviation authorities, to integrate UAVs with general air traffic in the near future. A progressive plan including a target date of 2028 for the full integration of drones into commercial airspace was published in June 2013 by the European RPAS Steering Group (European RPAS Steering Group, 2013; Hayes et al., 2014). Other aspects still to resolve include problems of data protection and infringements on the right to privacy. Additionally, the safety of the technology and its potential for accidents are viewed with increasing scepticism.

Technology is evolving fast and current limitations related with financial costs of platforms and sensors to make UAV systems operational will presumably not last very long. Platforms, sensors, software and other components are all rapidly becoming cheaper. Also, in contrast to satellite platforms, the sensors employed on a UAV can be changed throughout its lifetime, ensuring that they are always state of the art, and UAVs be retrofitted with newer, more innovative sensors.

5. MISSION AND PLATFORM CONSIDERATIONS

There are a range of factors to be considered when specifying an adequate unmanned aerial system for a certain application. Some general considerations whilst others are dependent and relative to the final purpose of a particular task the UAV must perform. The most relevant factors to account for when choosing a UAV system are listed and briefly described below.

5.1 Flying Time, Distance, and Area Coverage

The extent of the area to survey is crucial for selection of an adequate UAV, capable to cover the area in a reasonable time and with affordable power consumption. Among N-rotor platforms, DJI claims that the Phantom Quadcopter can fly at horizontal speeds of 10 meters per second (36 km per hour). However, given the battery life and energy required to travel vertically, it is not possible to fly more than 2-4 kilometres from the ground location origin. The maximum vertical speed is 6 meters per second, meaning it can rise to 30 m in as little as 5 seconds!

Local laws and regulations need to be checked before attempting any long distance flights, avoiding areas of possible conflict. The flying time – determined by the battery life (and/or backup)– limits smaller UAVs to short time and distance flights of about 6-8 minutes for older small platforms or 15-20 minutes for newer and larger platforms. For large area coverage, this could mean that the survey area has to be flown in parts or sections, something that may become impractical for UAV, and more cost and time-effective with traditional aerial platforms. Nevertheless, there are commercially operational fixed wing UAV platforms, such as Trimble Gatewing X100, capable of long flights covering large areas, which are considered more useful for surveillance and mapping activities including pipeline monitoring. Gatewing X100 has a cruise flight speed of 75 km/h, and flying at a height of 150 m it can cover 1.5 km^2 in 45 minutes acquiring 5 cm data. In general larger platforms can carry larger payload—including battery power. It must also be noted that developments in battery technology (details in section 6.5) will likely facilitate longer flight times, and greater distance and aerial coverage capabilities, even for small UAV platforms. Smaller platforms offer a flexible and low-cost means for the frequent capture of imagery to monitor small areas, whilst larger platforms can be used for larger area coverage, with some fixed-wing aircraft able to cover up to 10 square kilometres.

5.2 Flying height and ground control

Realisable flying heights for UAVs depend very much upon the type and size of the platform, the 'fuel', and the means of control. In the case of large drone-based systems the flying height can be over 9000 m. Some small platforms can climb to 600-700 m although most are restricted by the control unit typically to heights below 400 m, when the control signal is lost. Generally small platforms do not need to fly at such high altitude: for small area surveys where high resolution imagery is required, the flying height may be only around 5-10 metres. For example, in order to achieve 3.3 cm Ground Sampling Distance (GSD) imagery, a UAV may only be required to fly at 100 m high. As the flying height increases, the area coverage increase, and the image resolution decreases, depending on the camera resolution.

For ground survey work, the imagery needs to be geo-corrected. A network of Ground Control Points (GCP) accurately surveyed with a GNSS system (e.g. GPS) or identified in precise map source are necessary for accurate location. GPC are usually markers placed in a regular network on the ground and may comprise a post plus a cross (and number) visible on the aerial photograph. Each aerial image acquired has to be corrected to a true position on the Earth's surface with the aid of digital image processing software. The correction process removes the distortions in the X, Y and Z coordinates. Both geo-correction (2D) and ortho-correction (3D) are possible.

5.3 UAV altitude control

The flying height of a UAV depends on the characteristics of the platform and mission, but is determined in particular by the propellers and the payload. Maximum flying time decreases when flying height increases. Because the rotors spin faster to get higher altitude, the motors and the entire system become hotter during the high flights. There is a noticeable decrease in performance when going higher than 3000 m above sea level. However, this is unlikely to be a problem in the UK where 400 feet is the maximum permitted flying height.

In practice, it is advisable to maintain constant altitude during the data capture phase of the flight (either stills or video), in order to obtain consistent imagery and to minimize the need for complex post-processing of the imagery. Most UAV platforms – regardless the size – are now very stable and the height or altitude can easily be monitored through the use of an altimeter. The altimeter reading can be displayed on an FPV (First Person View) display monitor. Controlling the height of the UAV is usually straightforward on a standard controller; it can also be done by using a slider bar on a mobile phone App (Figure 13).

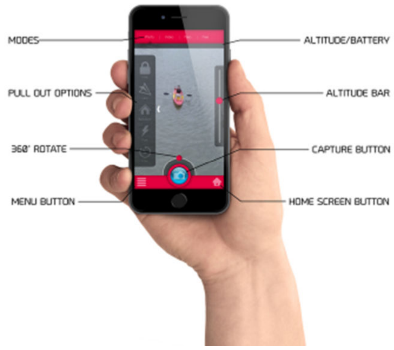


Figure 13. Mobile Phone App and Smartphone Interface showing simple altitude control

(http://www.ibtimes.co.uk/zano-tiny-clever-smartphone-controlled-helicopter-drone-that-takes-selfies-videos-1476806)

Most small UAV autopilots rely on control architectures that typically use various sensors (gyros, accelerometers, magnetometers, and GPS) and a computationally demanding estimation of the flight state. They tend to be complex, require a significant amount of processing power, and can be expensive. When altitude hold mode (AltHold) is selected on a UAV controller, the throttle is automatically controlled to maintain the current altitude. Roll, pitch and yaw operate the same as in *Stabilize* mode, meaning that the pilot directly controls the roll and pitch lean angles and the heading. Automatic altitude hold is a feature of many other flight modes. A light controller uses a barometer which measures air pressure as the primary means for determining altitude (i.e. pressure altitude) and if the air pressure is changing in the local flight area due to extreme weather, the platform will follow the air pressure change rather than the actual altitude, unless other means are enable (e.g. SONAR).

As an example, the AR.Drone 2.0 platform has pressure sensors on-board that provide stability and will automatically correct and maintain a still position in the air regardless of altitude and winds up to 15 m/h. A new algorithm has recently been created to allow the AR.Drone 2.0 interpreting measurements when hovering over different terrain and conditions.

Aside from simple solutions that are the most common solutions for many UAVs – at least the smaller ones - some research papers focus on newer and simple approaches to altitude measurement and control (e.g Hua et al., 2013; Cai et al., 2013).

5.4 Manual and automated launch / landing

Many small UAVs (e.g. N-copters) can take-off and land on the ground with or without the aid of a landing pad. Some can also be hand launched and landed, making them very flexible and easy to use. Larger and more sophisticated UAVs (N-rotor or fixed wing) require some form of launching device to facilitate the take-off of the platform. These pieces of kit are additional equipment that makes the logistics of the mission less easy and flexible. Safe retrieval is important and whilst many platforms can be easily landed in areas of grass or bushes, this is not always possible. In order to prevent damage to the sensors and aircraft, recovery options including parachute and homing systems have been developed for recovery.

5.5 System Failure and Retrieval

System failure is not impossible or unlikely, and whilst most UAV platforms are now ReadyTo-Fly (RTF) systems, problems can arise including rotor failure, fly-aways, and motor malfunction amongst other things. Depending on the severity of the problem, UAV platforms could be destroyed or damaged beyond repair together with the on-board sensors and electronics. However, most UAV kit is built robust, and both easy and cheap to repair. Operators should have ready to use spares (e.g. rotors, nuts, bolts) and ensure rigorously conducted thorough checks of the system and platform prior and in between each flight.

Whilst most fixed wing aircraft can glide to the ground, N-copters are more likely to drop like a stone if a rotor fails. However, hexacopters and octacopters are more easily controlled to a safe landing - should a rotor fail - than quadcopters. Today, with RTF platforms and sophisticated radio control (RC) and autonomous flight modes being available, fly-aways are unlikely. Controlled ascent and descent modes are enabled, as well as a return to base option when battery power drops below a certain level. Operating with FPV monitors helps avoiding UAV collision with objects such as trees, and there is also some functionality that prevents collision and the platform going beyond a specified distance (both horizontally and vertically) from the operator. In cases where the UAV is likely to be flown over water bodies or at the coast, ditching or landing in the water should be avoided, as most UAV platforms, power sources, electronics, and on-board equipment are not be waterproof, and the kit may therefore need to be written off. There are some waterproof and floating UAV platforms available but in most cases the UAV platform is not designed to float. The additional motors of hex- and octacopters permit single motor out recovery and provide for smoother flight for photo uses. In those cases, they need to use smaller propellers because of motor to motor clearance which is less efficient and results in shorter flight times.

5.6 Flying Conditions

Most UAVs are restricted by the environmental flying conditions they can operate in. As most platforms are not waterproof, this means that for the most part these platforms and their sensors cannot be flown in anything other than dry conditions, especially for most electric powered UAVs. If a UAV gets caught in the rain it is generally best to land as soon as possible.

Recommendations for many small N-rotor platforms are to fly up to a maximum of a light breeze. However, tests suggest that such platforms can actually be flown in a moderate breeze, although the aerial imagery captured may ultimately be compromised by the instability of the yaw, pitch, and roll of the platform. Such small platforms may also be damaged by strong gusts. Some manufacturers claim that wind speeds up to 11 m/s will still allow for stable video with no post survey control needed. In addition, light rain and drizzle are tolerable although for most applications the rain spoils the shot.

5.7 Mission planning

Mission planning software (http://ardupilot.com/downloads/?did=82) is now widely available providing the basis for small UAV platforms to fly fully autonomously. Increasingly these are designed to be plug and play and can be determined using waypoints 'on the fly' or via pre-planning for an aerial sortie. Many e.g. Mission Planner and Droid Planner (see section 3.3.2 in this report) are widely available for use on tablets and smartphones and can be used to plan repetitive and large area coverage flights for N-copters and fixed wing UAVs.

5.8 Operation and control

In the past, most radio control model aircraft required considerable skills for launching, flying and landing and was regarded as a specialist activity. Today, part of the attraction and rapidly growing use of the small UAV platforms has been driven by developments in the technology allowing virtually anyone to fly – with a shallow learning curve –small quadcopters, and more recently the autonomous fixed wing aircraft increasingly used for aerial survey work. These days many popular UAVs come ready to fly, the platform can fly in an autonomous mode in which the aircraft is guided via GPS to pre-programmed waypoints. RTF aircraft can easily be flown horizontally and vertically along a flight line using a monitor or goggles which display the view over which the UAV is flying, and include altimetry, battery power and other useful parameters. Simple radio-controlled hand-held controls, operating in the 36 MHz band or the 2.4 GHz bands, with Mode 1 and mode 2 controls – left and right joysticks – allow the UAV to be controlled easily.

Wi-Fi offers the bandwidth and range to transmit video at reasonable quality and minimal latency. Motorized gimbals, like high-quality cameras, have been miniaturized, and computerized flight controllers have diminished the pilot learning curve.

Computerized flight-control systems e.g. Naza manage everything that occurs during the flight, from relaying user inputs sent to the receiver (RX) to affecting the appropriate movement response in terms of throttle, pitch, and yaw to factoring GPS, gimbal, compass, and sensor data to determine flight attitude and make appropriate assisted-flying adjustments. The flight controller is literally the brains of the aircraft, though the sophistication of these brains can vary. The DJI Naza-M system, in particular, is currently at the advanced end of the flight controllers' spectrum. It takes GPS, compass, gimbal, and altimeter data and uses that information to provide full autopilot redundancy, if required. Perhaps the most important feature that GPS-based flight controllers offer for beginners is Return to Home Failsafe. Return to Home is the quadcopter's ability to automatically fly back to a pre-specified "home point" if contact with the transmitter (TX) is ever lost. More basic flight controllers that lack GPS data, on the other hand, might only provide basic stabilization safeguards.

In addition, it uses GPS coordinates to hold the aircraft in a fixed horizontal and vertical spatial position, as much as possible, whenever the pilot releases the controls. Nevertheless, these platforms are still sophisticated, and require practice and experience, maintenance and calibration.

5.9 Digital image processing software

The photography acquired by UAVs can be visually interpreted with aerial photo-interpretation techniques. Digital Image Processing (DIP) software, much of it now low-cost, can also be used to geo-correct and mosaic the photographic prints or images together as the basis for onscreen interpretation and the mapping of thematic information for subsequent input to a GIS. The lower cost of PCs and accompanying hardware (e.g. storage media, scanners, printers and software) provides opportunities to capture, store, process and map the data in-house on a regular basis.

Digital image processing (e.g. geometric and radiometric corrections) can be performed with standard or specialised DIP software. Furthermore, there is now a small range of UAV dedicated software packages available specifically aimed at UAV image acquisition and correction, which have similar functionality and better price. A few examples of UAV dedicated software are listed below:

Pix4D: (http://pix4d.com/solutions/) has developed software that automatically combines raw images captured by lightweight UAVs to produce accurate measurements and visualisation of the environment. This enables timely, on-demand local 3D mapping. Pix4D automatically turns a large number of images into accurate, 2D maps (orthomosaics) and 3D models (digital elevation models).

MosaicMill: (http://www.mosaicmill.com/products.html) provides photogrammetric tools for both UAV operators and conventional manned aircraft operators. EnsoMOSAIC creates orthomosaics, 3D models, XYZ point clouds from images, GPS positions and camera calibration parameters. The software has capacity for camera calibration. The output products are ready to open in any GIS software for further development.

AirPhotoSE: (http://www.uni-koeln.de/~al001/airphotose.htmlv) AirPhoto Special Edition is free and open source software for the geometric rectifcation of oblique aerial images and generation of orthophotos. Provides high flexibility of input /output formats and it is compatible with GIS software.

Agisoft Photoscan Pro: (http://www.agisoft.com/). Photoscan Pro allows generating high resolution georeferenced orthophotos (up to 5 cm accuracy with GCP) and detailed DEMs. A fully automated workflow enables non-specialists to process thousands of aerial images on a desktop computer to produce professional class photogrammetric data.

6. DEVELOPMENTS IN UAV AND RELATED TECHNOLOGIES

This section focuses on some of the technological developments now underway that will affect the development and suitability of UAV and related technology to oil and gas pipeline monitoring, and which will in some cases or in combination significantly affect and extend the current capabilities to smaller, lower cost platforms and sensors.

6.1 Hot Swappable Sensors

Whilst some of the smaller UAV platforms allow for the mounting of small still and video cameras, such as the GoPro and iLook, the camera mountings are still quite crude and necessitate time consuming maintenance to facilitate camera operation and changes. With the drive towards more sensor capability, more emphasis is being placed on the availability of mechanisms to allow for the rapid change-over or exchange of different sensors on the UAV platforms. Known as hot swappable sensors, such capability allows a single UAV ‘air frame’ to carry a wide range of sensors, providing multi-sensor capability.

For example, Aeromapper UAVs (http://www.aeromao.com/aeromapper_uav) using a hot-swappable mount can carry a wide range of sensors either on their own or in multiple configurations. Other UAV manufacturers such as QuestUAV have developed hot-swappable sensor pods designed to contain one or more sensors for ease of exchange. Similarly, Tekever Autonomous Systems (http://autonomous.tekever.com/ar4/specs.html) have developed a hot-swappable sensor payload capability for their AR4 Light Ray system for Electro-optic, Infrared, Night Vision and Low Visibility sensors. This capability will make these and other UAV platforms more flexible in practice.

6.2 Platform Development

UAV platforms are continually being developed. With the growing popularity and demand for RTF platforms and the growth of the small autonomous UAV, frequent developments and improvements are being revealed almost every day. These include the nature, size, durability, and materials used for the construction of the platform, the capacity of the motors and batteries, and the load capacity. Many mainstream manufacturers are now issuing upgrades and new models within a very short period of time, which include significant developments of the technology. DJI and 3D Robotics, for example, are revealing new and more capable platforms with the capacity to carry higher payloads and to offer the means to fly professional photography and video. Some specific developments in relation to platforms are those that combine new technologies in a safe package which provides mechanical protection for target collisions, protecting the electronics, rotors and on-board sensors e.g. WorkFly's Flying Sensor S3 (www.workfly.net), and Riegel's RiCopter with an integrated Riegl VUX-1 laser scanning system (www.riegl.com). More recently, with the popularity of GoPro cameras on many UAV platforms, GoPro are reported to be developing their own UAV platform.

6.3 Multi-UAV Configuration (Swarms)

The relatively low purchase price and operating cost together with automated flight capability opens up the possibility of using several UAVs simultaneously to perform a survey task. The capacity of the UAV to follow a precision flight path in both altitude and position helps minimising the overlapping extent of images. For intercommunication the UAV can use the on-board wireless LAN to communicate with nearby UAVs, in a wireless mesh network, with only a minimum number of UAVs maintaining either satellite, or, mobile phone based communication links. A swarm of UAVs will greatly reduce the time taken to perform some surveys, with parallel operation of imaging and sensor systems, all operating at maximum data transfer rates. The approach also increases tolerance to fault tolerance, because if a sensor on a UAV fails it can return to base and another UAV could continue with the work without much interruption.

Any swarm configuration (i.e. number of UAVs and distances between them) can be set up to fulfil the application requirements. The goal is to optimize the coverage in adequate time, providing fine data. For oil and gas pipeline monitoring a swarm of UAV could be configured, each carrying a different type of sensor (e.g. visible camera, lidar) for acquisition of complementary data.

6.4 Cloud-Based Data Storage

Current opportunities to gather spatial data, much of it in the form of imagery and video, necessitate somewhere to store the data. For relatively large airborne platforms, the storage of huge amounts of data is not a serious problem. For smaller platforms, however, particularly the current off the shelf systems, on-board storage capacity is severely limited by the space on board the platform, and the carrying capacity when one takes into account all the components that make up the platform including the sensor mountings, batteries, storage devices and media, and antennae. Some additional benefits have been gained by smaller higher capacity storage media. For most UAVs carrying small cameras, the storage for the stills and video is the SD or MicroSD cards, which come in various capacities and read/write speeds. These cards are all high capacity, small, and lightweight.

As discussed earlier, many small platforms are constrained by their ability to lift the sensor technology usually in terms of the battery power and the flying time. Whilst battery life and lifting capacity can be overcome using a larger platform, the advent of Wifi connections to external networks and cloud-based storage has somewhat removed this constraint on the smaller UAVs where space and additional weight render the potential of some UAV for certain applications. Providing connectivity is possible, cloud-based storage should alleviate some of the requirements for on-board storage capacity, particularly for video capture (as video files require large storage capacity), particularly where space and payload are at a premium.

6.5 Battery Technology and other UAV Fuel Sources

The majority of popular UAVs use some kind of battery as a source of primary or at least back-up power. Selecting an adequate battery is key for achieving the desired vehicle operational parameters with reliability. Among the limitations of currently existing batteries for use in small UAVs, the weight, speed of re-charge, discharge rate, and cost are most relevant. Whilst larger batteries are available, the capacity of the platform to lift and hold larger or multiple batteries is a major limitation. However, there is considerable effort driven to developing battery technology with rapid advancements, for instance the ratio capacity to size is increasing which facilitates more power consuming activities, like longer flights and heavier payloads. Among electrochemical battery technologies Lithium Polymer and Lithium Sulphide have particularly been highly developed.

Lithium Polymer (LiPo) batteries are a particular type of Lithium Ion batteries in which the material used as separator is a micro-porous polymer covered in an electrolytic get that also serves as a catalyst reducing the energy barrier in the chemical reaction between cathode and anode. The solid polymer flexibility enables construction of batteries in various shapes and sizes. LiPo batteries are over 20 % lighter than the equivalent electrochemical cylindrical cells, and are energy denser than other Lithium Ion batteries—also more expensive. The voltage of a LiPo cell varies from about 2.7 V (discharged) to about 4.2 V (fully charged) and care should be taken to protect them from overcharge.

Lithium Sulphide (LiS) batteries are developed by Sion Power (www.sionpower.com) and have achieved major breakthrough results by the unique merging of sulphur and lithium chemistries. For In high power applications, LiS has nearly the same rate capability as nickel cadmium and nickel metal hydride but has around one-fourth the weight. In addition, the LiS technology starts with a lower material cost than Li-Ion or LiPo batteries. The voltage of a LiS cell varies from about 1.7 V (discharged) to about 2.5 V (fully charged). LiS batteries are a major improvement in battery technology for UAVs where battery weight has been reduced by up to 60%. Table 3 compares the parameters of Li-Ion battery and Li-S battery configurations to power UAVs.

Table 3. Comparative configuration of Li-Ion battery versus Li-S battery for UAVs

	Li-Ion	Li-S
Configuration	7S3P	12S3P
Cell capacity	2.2 Ah	2.2 Ah
Pack weight (kg)	1.075	0.640
Energy density (Wh/kg)	155	260

Metal-Air batteries technologies (e.g. Zinc-Air, Aluminium-Air, Lithium-Air) are being developed. These batteries have valuable qualities that will benefit the UAVs industry, e.g. high density power. Metal-Air batteries are energized only when atmospheric oxygen is absorbed into the electrolyte, after removal of a protective seal. For instance, a Zinc-Air battery usually reaches full operating voltage within five seconds of being unsealed. The cell voltage for the chemistry is theoretically capable 1.65 V however almost all designs are optimised for less than 1.4 or 1.3 V in order to achieve longer lifetimes.

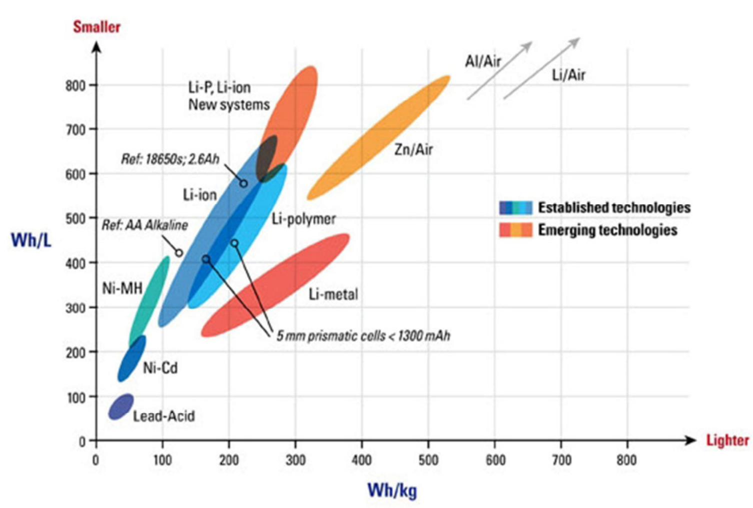


Figure 14. Ragone chart showing performance of various battery technologies. Source: www.uoregon.edu

Graphene is perhaps the most promising material for battery development. Graphene is a very light material discovered in 2004, which is a carbon derivative stronger than diamond. Graphene has very high conductivity capacity and its electrical properties are ideal for developing supercapacitors, i.e. high capacity batteries with quick charging speed. Unlike electrochemical batteries, capacitors (and supercapacitors) minimise the loss of energy by heat and internal resistance, considerably augmenting their efficiency. Graphene batteries are still not commercially available, but there is considerable research and prototypes are being developed, including a 3D printed battery by Graphene 3D Lab (www.graphene3dlab.com/s/home.asp).

Other sources of energy used by a few UAVs are **fuel cells** and **solar power**. Some even use new technologies such as **micro-generators**, **micro-turbines**, and **chemically powered systems** that may replace batteries in the future. Nevertheless, battery technology is far from becoming obsolete and new designs introduced by battery manufacturers now offer relatively light, high capacity, and reliable sources of power.

Horizon Energy Systems (an energy company based in Singapore) has developed the AEROPAK technology. At the core of AEROPAK technology is a polymer electrolyte membrane **fuel cell**. The fuel cells are air cooled and self-humidified. AEROPAK uses dry fuel cartridges with four times more power than Lithium batteries. Cartridges are refilled with water and battery charges are not needed.

Solar power can be used as another source of fuel for UAVs, usually for large size platforms with long flying missions. Solar cells combined with LiPo and LiS batteries constitute a day/night power solution for several days of flight. There are currently three different types of solar cell technologies: crystal silicon, amorphous silicon, or compound semiconductors. With initial prototypes staying up in the air for a few hours, a new generation of UAVs could optimize solar cell technology and power management to spend years in the air in operation.

All technological developments directed to increase the UAVs capacity for longer flight times are of great interest. Among these, recharging power during flight seems to be an interesting goal. Lockheed and Martin and LaserMotive developed a **laser system** for in-flight power charging. Similarly, Somatis Technologies (based in Los Angeles, US) is working on a **kinetic energy composite** that turns the interaction of wind pressure and vibrations into an electrical power energy source and could triple battery life for UAVs. The key is piezoelectric composites, a material which helps convert mechanical energy into electrical energy. Skysense has developed a landing pad to charge almost any n-copters, by contact of the drone with the gold-plated area, thanks to their patent-pending technology.

6.6 3D Printing

The technical term for 3D printing is additive manufacturing (AM). In contrast to the traditional manufacturing process taking a piece of raw material and cutting or grinding it down to form the component, AM creates a three dimensional object by layering materials under computer control. *Stereolithography*, *selective laser sintering*, or *fused deposition modelling* are technologies similar to AM, based on the same layering foundations. 3D printed objects can be of almost any shape or geometry and are produced from a 3D model or other electronic data source by an industrial robot (the 3D printer).

3D printing technology emerged in the 1980s, but only recently has it become more common and feasible, thanks to improved printing resolution and strength of materials. This technology is evolving very rapidly and it is envisioned to support user needs in a very short return time. For instance designers could make a blue print for a client or user and in a few hours send a digital 3D prototype for printing in the client's 3D printer. Task specific UAVs will presumably be designed attending particular mission needs, then be printed, used and disintegrated. Already many of the third-party spares, parts and modifications for UAVs are available as 3D printed products, e.g. for the DJI Phantom 1 and 2 many modifications are available from www.shapeways.com.

Among recent initiatives for 3D printed UAVs is the Advanced Manufacturing Research Centre (AMRC) in collaboration with England's University of Sheffield and Boeing where the advent of cheap 3D printing of drone parts, open-source software and cloud computing has led to new start-ups such as Skycatch, a company providing surveillance services through UAVs.

6.7 GIS

Geographic Information Systems (GIS) are used for data storage, retrieval, and visualisation. In addition to remote sensing, digital image processing (DIP) and other geospatial technologies, GIS provide the means to store, manage, integrate and visualise spatial data and information from multiple sources including UAV platforms. In the context of oil and gas pipelines, GIS provides the means by which it is possible to manage a wide range of datasets, both historical and new, and with the aid of the Internet to share data and more importantly information with others. The potential of such a system has been demonstrated in the past by products such as the NW Ethylene Pipeline Management System developed by RSK (Kemp et al., 1993). Other examples are provided by the

Aratos Pipeline Surveillance System which includes a GIS system for the visualization of pipeline systems and software for the processing of satellite images).

6.8 Costs

The price of small civilian UAVs varies widely depending on the features and equipment included. Some simple low-cost UAV platforms can be purchased for a few hundred pounds (e.g. DJI Phantom, Parrot AR drone) or a thousand pounds (e.g. 3D Robotics IRIS), while high capability and sophisticated units cost more than ten thousand pounds (e.g. Penguin B, Gatewing X100). To this must be added the cost of the control equipment, cameras and sensors, the FPV, tablets, gimbal, as well as storage, training and insurance etc. Nevertheless the cost of a functioning platform can be quite low, and depending on the application, the initial investment in a UAV is often far outweighed by other cost efficiencies created by the addition of this technology. For example, a single engineer who is licensed to operate a UAV can replace a team of technicians who might otherwise spend hours securing, accessing, and assessing a dangerous or remote site. Mobile applications for smart phones or other devices can live stream video from a UAV's camera, and the operator can wear goggles to view in real time the site.

6.9 Security systems

The security of UAV flights sharing airspace with manned vehicles is crucial for civilian use of these platforms. Security will become increasingly important as more of these platforms, both civilian and commercial take to the skies. Multiple efforts are now being directed to improve emergency landing procedures, radio connections, sensor function, and the availability and use of *sense and avoid* technology that will facilitate access of UAVs to shared airspace.

The Mid-Air Collision Avoidance System (MIDCAS) is a multinational project supported by a consortium of 13 companies from Sweden, France, Germany, Italy and Spain, and funded by the European Defence Agency (EDA). This joint effort started in 2009 with the aim to contribute to the UAS integration in civilian airspace, proposing solutions for the UAS mid-air collision avoidance function that would be acceptable by the manned aviation by 2015. MIDCAS works to arrive at an international solution by developing an acceptable Sense and Avoid system (www.midcas.org).

7. PROPOSED UAV SYSTEM FOR MONITORING OIL AND GAS PIPELINES

From the coverage and discussion provided above in relation to UAV technology, and the various developments and examples of existing operational UAV-based solutions, it is clear that there are numerous options for monitoring oil and gas pipelines with a range of UAV platforms and sensors. Those options are dependent on the nature of the information that is required e.g. concerning the visual appearance of the pipeline itself or the potential impact of the hydrocarbon spill or leak on the visual appearance of the surroundings e.g. the vegetation or soil, or the spectral response in one or more portions of the electromagnetic spectrum. Different solutions might be valid to solve a single problem. For example, if there are changes to the colour of the pipeline above ground, it may be possible to utilise still/video image interpretation, or to apply simple image processing techniques to help extract such information visually. The same sort of approach may be applicable to data/imagery acquired in other parts of the electromagnetic spectrum, or to isolate ways to extract surrogate information that is indicative of the impacts of pollution and contamination e.g. changes in the thermal properties of the surrounding soil and vegetation. Changes to soil moisture, vegetation canopy properties, and leaf-colour and vegetation status may also be useful indicators of possible or actual leaks.

Whilst in some cases that kind of information could be obtained by walking the pipeline or pipeline route using visual observations or hand-held sensors, or flying the pipeline and surrounds using remote sensors, both options are costly for the need of frequent repetitive monitoring over long distances. Satellite imagery would be too coarse in spatial resolution, and also too infrequent. UAVs, by comparison, offer huge potential for oil and gas pipeline monitoring both above and below ground, which at the local scale can provide both visual and sensor-based image processed information to help identifying hotspots where there is an actual or potential leak of hydrocarbons. The high resolution data acquired has the potential to provide detailed information about the status of the pipeline and/or surroundings, at a fine scale. Depending on the type of platform (i.e. N-copter or fixed wing) there is also scope to utilise the hovering capability for monitoring, or the autonomous-based repetition of the largely linear pipeline route. As the payload capability increases it should also be possible to fly the pipeline with different sensors, including thermal which as mentioned in this report are well suited for detection and identification of leaks' temperature.

7.1 Considerations for specifications of a UAV system for monitoring oil and gas pipelines

The choice of an adequate monitoring system relies on a wide range of factors. Of paramount importance is the type of information required for the following up of the system (e.g. direct observation of the pipelines, acquisition of environmental indicators). The physical characteristics of the environment (e.g. accessibility, terrain roughness, distance to target pipeline) impose limitations to certain systems or configurations. When combined, information needs and environmental characteristics support the case for decisions about the optimal platform and equipment for the task.

Table 4. Considerations for selection of UAV system for oil and gas pipeline monitoring

Observations needed	The pipeline system can be monitored by direct detection of hydrocarbon / gas leaks or indirectly by monitoring indicators or surrogates of leaks (e.g. change in soil or vegetation condition).
Terrain conditions	Flat terrain simplifies UAV navigation. Constant height and speed is the best option for easiness of data processing Alternatively, to monitor pipelines in heterogeneous conditions, an adaptable navigation system is necessary.
Flight Distance	A strategic design of the flight aims for efficiency and cost savings. Flying distance and flying time depends on the characteristics of the network of pipelines to monitor (e.g. length, connections, risk points). One-way flight along the pipeline route with recovery stations at both ends (or in intermediate stations) is superior to return flights.
Legislation	National regulations control the options for use of one type of UAV or another. Currently the use of UAVs is still relatively restricted. As a result of a more

	pressing demand for applications it is expected to be developed further.
Platform	The type of platform to choose depends on what is required of the exercise e.g. flying the entire pipeline from one end to the other on a regular basis would require an autonomous fixed wing UAV carrying one or more sensors or a video camera, whilst hot spot monitoring (with or without the need for the pipeline over flight) would be better suited to an N-copter deployed at intervals along the pipeline for close-up monitoring of a leak or damage to the surroundings carrying an small still/video camera system.
Sensor	The sensor or sensors onboard the UAV should be optimized for direct or indirect detection of the hydrocarbons or gas leaks. These should be functional or adaptable regardless of weather conditions. Depending on the purpose of the task for oil and gas pipeline monitoring, one or more sensors may need to be carried on the platform
Payload weight	The platform has to carry the sensor and auxiliary equipment (e.g. GPS and INU for navigation).
Data processing	Processing of data acquired to generate useful information usually involves: Geometric correction. An exact spatial correspondence of features captured in images with reality and other data sets is crucial. Radiometric calibration. Reliance of repetitive surveys is based on perfect radiometric calibration of measurements.

Based on the information researched and summarised in the previous sections, various scenarios are now proposed summarizing the recommendations for the deployment of UAV systems for monitoring oil and gas pipelines. Different scenarios are described below for which a particular UAV would be suitable.

7.2 Monitoring scenarios

Scenario 1: Proximity survey / visual identification of pipe damage

For observation of nearby pipelines requiring short distance flights and close and detailed observation of difficult positions, a micro N-copter with high capacity to manoeuvre is a good option. This is a typical operation for assessment of risk points like junctions or for evaluation of new features in the pipeline network. Powered by batteries for the flight and to supply the sensor, the operator should be equipped with extra batteries for replacement. The required flying altitude is low, as the mission focus on observation of pipelines on the ground.

UAV scenario 1: small and lightweight low-altitude UAV	
Flying altitude	Very low (< 50 m)
Payload	< 7 kg
Endurance	< 1 h
Platform	N-copter with hovering capacity and high maneuverability
Sensor	High resolution video camera with on the fly transmission

Scenario 2: Short distance survey / visual identification of leak

For inspection of a short to medium length pipeline (up to various km depending on local legislation) an altitude of around 100 m, which is typically below clouds, might be appropriate. This might be a repetitive monitoring mission, and will benefit from a fixed flying plan, determined by a number of way points. An adequate platform is a fixed wing UAV, equipped with visible and NIR still/video camera and possibly a lidar. Data should be recorded for comparison with previous and future surveys and change detection.

UAV scenario 2: small and lightweight low-altitude UAV	
Altitude	Low (< 100 m)
Payload	< 25 kg
Endurance	5-6 h
Platform	Fixed wing
Sensor	Optical or NIR camera, lidar

Beyond small UAV platforms, adequate for short distance and detail flexible surveys, other UAV systems can be considered for monitoring oil and gas pipelines, which in some occasions are superior to other manned aerial options (e.g. danger, cost).

Scenario 3: Long distance survey / automatic sensing of oil properties

Although beyond the capacity of small UAV platforms, a more difficult stage in monitoring oil and gas pipelines can also be performed by larger UAV systems. Long pipelines in remote areas need periodical observation for detection of damage or malfunction.

UAV scenario 3 – medium-size and medium-weight mid-altitude UAV (MALE)	
Altitude	Medium (>1000m)
Payload	200 kg
Endurance	30 h
Platform	Medium size long endurance
Sensor	Multisensor: radar, lidar, multispectral camera

This type of UAV is operated in the controlled airspace and must, therefore, be implemented in a full Air Traffic Control environment and can be powered by a wide variety of engines and motors, as well as fuel and battery. Since the UAV is operated above 1000 m is, i.e. in general, not below clouds, a radar (SAR) sensor is desirable, which could be complemented by an optical/IR sensor system. This, in turn, requires an appropriate payload capacity. The image processing and feature extraction efforts are more complicated than previous scenarios, since radar data require more sophisticated processing steps and is better exploited if combined with data from other sensors.

8. SUMMARY AND CONCLUSIONS

Oil and gas transmission pipelines require continuous monitoring for maintenance and safety, because there is always a chance of equipment failure or accident that would jeopardize the system functioning and the security of the environment. UAVs are a relatively new technology, emerging as an opportunity to supplement and sometimes substitute current monitoring systems. UAVs technological solutions are flexible and adaptable, and with demonstrated capacity to obtain valuable data at short to medium spatial scales to alert of risks and to inform management decisions.

The choice of UAV system should be led by precise identification of the project information needs, because there are multiple design options and specialized equipment to approach unique problems. Extensive areas to survey systematically are better covered with fix wing platforms and automatic flight design, whilst n-rotor platforms provide more flexibility in shorter missions, thanks to the hover capacity and high manoeuvrability. An important decision concerns the type of sensor to be carried by the aerial platform, since the sensor determines the type of data acquired and the obtainable information, as well as the need for specific mechanical designs (e.g. gimbal). Miniaturization of sensors (e.g. lidar, hyperspectral) is an ongoing technological goal, being payload weigh and battery power key limitations for full capability of UAV systems in mapping and monitoring projects.

UAV and associated technologies like data storage and transmission or image processing software are currently developing by the day, improving designs and capacity very quickly. Progress in platform design and control, power source, sensors and accessories foretell a promising near future with ample opportunities for the use of UAV in oil and gas daily monitoring. National and international regulations advance at varying speed, with the goal to assure a safe incorporation of UAVs into common flying space without violating privacy and without risking security.

UAVs have demonstrated, through research and operational cases, the capacity to make easier some oil and gas pipelines monitoring tasks, in remote and difficult areas, as well as in repetitive operations. A number of low-cost and high cost off-the-shelf technological solutions are available, all of which have potential for undertaking the monitoring missions, by surveying and mapping the pipelines and the environment.

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10. APPENDICES

Appendix 1 - Examples of commercial sensors designed for UAVs

Appendix 2 – UK CAA specific regulation for unmanned aerial vehicles

Appendix 3 - List of aerial remotely piloted aircraft systems in the UK

Appendix 1. Examples of commercial sensors designed for UAVs

PASSIVE SENSORS

	Name	**Weight**	**Company**	**Comment**
VISIBLE	*Nocturn U3*	0.15 kg	Photonis www.photonis.com	42 x 41 x 58 mm
	Nocturn MD	0.05 kg		34 x 37 x 25 mm
	Nocturn GV	0.18 kg		47 x 47 x 57 mm
MULTISPECTRAL	*ADC Lite*	0.20 kg	Tetracam www.tetracam.com	0.5-0.9 µm (3.2 Mp)
	ADC Micro	0.09 kg		0.5-0.9 µm (3.2 Mp)
	ADC Snap	0.09 kg		0.5-0.9 µm (1.3 Mp)
	sCMOS	1.4-1.9 kg	CONDOR Vision http://www.cmosvision.com	5 bands (4-10 µm)
SWIR	*SWaP*	0.027 kg	Sensors Unlimited www.sensorsinc.com	InGaAs component
	BobCat	~0.4 kg	Xenics www.xenics.com	55 x 55 x 72 mm (0.9-1.7 µm)
HYPERSPECTRAL	*Micro Hyperspec*	0.6-1.1 kg	Headwall Photonics www.headwallphotonics.com	Up to 370 bands
	Nano Hyperspec	0.6 kg		270 bands
	OCI-UAV-1000	0.27 kg	BaySpec www.bayspec.com	Pushbroom
	OCI-UAV-2000	0.36 kg		Snapshot
	UHD 185	0.13 kg		125 bands
THERMAL	*FLIR Quark 640*	0.03 kg	FLIR www.flir.com	IR band 7.5-13.5 µm Lenses: 6-35 mm
	Tamarisk 320	0.03-0.16 kg	DRS Technologies www.drsinfrared.com	IR band 8-14 µm Lenses: 6-35 mm
VIDEO	*Hero*	0.11 kg	GoPro www.gopro.com	59 x 41 x 30 mm 12 Mp
	iLook	0.12 kg	Walkera www.walkera.com	59 x 41 x 21 mm

ACTIVE SENSORS

	Name	**Weight**	**Company**	**Comment**
LIDAR	*VUX-1*	3.6 kg	Riegl www.riegl.com	FOV = 330° Precision 10 mm
	YellowScan	2.2 kg	L'Avion Jaune www.yellowscan.lavionjaune.com	FOV = 100° 80k shots/sec
	HDL-32E	1.2 kg	Velodyne www.velodynelidar.com	FOV = 360° 600k shots/sec
	VLP-16	0.6 kg		FOV = 360° 300k shots/sec
	UTM-30LX	0.4 kg	Hoyuko www.hoyuko.com	FOV = 270° 40k shots/sec
RADAR	*YINSAR*	< 2 kg	BYU www.byu.com	70 × 85 × 70 mm Not commercial
	NanoSAR-C	< 1.5 kg	IMSAR www.imsar.com	Ku, X, UHF, UWB

Appendix 2. UK CAA specific regulation for Unmanned Aerial Vehicles

A ***Small Unmanned Aircraft*** (SUA) is defined in *Article 255* of the Air Navigation Order (ANO) 2009:

> Small Unmanned Aircraft means any unmanned aircraft, other than a balloon or a kite, having a mass of not more than 20 kg without its fuel but including any articles or equipment installed in or attached to the aircraft at the commencement of its flight.

A ***Small Unmanned Surveillance Aircraft*** (SUSA) is defined in *Article 167(5)* of the ANO 2009:

> A small unmanned surveillance aircraft means a small unmanned aircraft which is equipped to undertake any form of surveillance or data acquisition

CAP393 *Air Navigation: The Order and the Regulations*

Article 166. Small unmanned aircraft (SUA)

(1) A person must not cause or permit any article or animal (whether or not attached to a parachute) to be dropped from a small unmanned aircraft so as to endanger persons or property.

(2) The person in charge of a small unmanned aircraft may only fly the aircraft if reasonably satisfied that the flight can safely be made.

(3) The person in charge of a small unmanned aircraft must maintain direct, unaided visual contact with the aircraft sufficient to monitor its flight path in relation to other aircraft, persons, vehicles, vessels and structures for the purpose of avoiding collisions.

(4) The person in charge of a small unmanned aircraft which has a mass of more than 7kg excluding its fuel but including any articles or equipment installed in or attached to the aircraft at the commencement of its flight, must not fly the aircraft:

(a) in Class A, C, D or E airspace unless the permission of the appropriate air traffic control unit has been obtained;

(b) within an aerodrome traffic zone during the notified hours of watch of the air traffic control unit (if any) at that aerodrome unless the permission of any such air traffic control unit has been obtained; or

(c) at a height of more than 400 feet above the surface unless it is flying in airspace described in sub-paragraph (a) or (b) and in accordance with the requirements for that airspace.

(5) The person in charge of a small unmanned aircraft must not fly the aircraft for the purposes of aerial work except in accordance with a permission granted by the CAA.

Article 167. Small unmanned surveillance aircraft (SUSA)

(1) The person in charge of a small unmanned surveillance aircraft must not fly the aircraft in any of the circumstances described in paragraph (2) except in accordance with a permission issued by the CAA.

(2) The circumstances referred to in paragraph (1) are:

(a) over or within 150 m of any congested area;

(b) over or within 150 m of an organized open-air assembly of more than 1000 persons;

(c) within 50 m of any vessel, vehicle or structure which is not under the control of the person in charge of the aircraft; or

(d) subject to paragraphs (3) and (4), within 50 m of any person.

(3) Subject to paragraph (4), during take-off or landing, a small unmanned surveillance aircraft must not be flown within 30 m of any person.
(4) Paragraphs (2)(d) and (3) do not apply to the person in charge of the small unmanned surveillance aircraft or a person under the control of the person in charge of the aircraft.
(5) In this article 'a small unmanned surveillance aircraft' means a small unmanned aircraft which is equipped to undertake any form of surveillance or data acquisition.

Appendix 3. List of aerial remotely piloted aircraft systems in the UK

Source: ARPAS UK (http://arpas.co.uk/arpas-members-list/)

Organisation	Town	County	Website
iRed Ltd	Emsworth	Hampshire	www.iredltd.co.uk
Thomas Haywood Photography	Edinburgh	Lothian	www.thomashaywood.co.uk
Dataq Technologies Ltd	Warwick	Warwickshire	www.dataqtechnologies.co.uk
Dimension Media Ltd	Burghfield Common	Berkshire	www.dimensionmedia.co.uk
AM-UAS	Kidlington	Oxfordshire	www.am-uas.com
Rotorvista	Weston-super-Mare	Somerset	www.rotorvista.co.uk
Halo Aerial Imaging	London	London	www.haloaerialimaging.com
OverView Aerial Photography	Castle Douglas	Dumfries	Awaiting Link
Kurnia Aerial Photography	Mablethorpe	Lincolnshire	www.kurniaap.webeden.co.uk
ClearSky Aerial Imaging	Stroud	Gloucestershire	www.clearskyaerialimaging.co.uk
Hightakes.com	London	London	www.hightakes.com
Cloud 12	Berkeley	Gloucestershire	www.cloud12.co.uk
The Drone Gus	Calne	Wiltshire	www.thedroneguys.com
Bexcopter	Dursley	Gloucestershire	www.bexcopter.co.uk
DeeJGee Research Consultancy	Glasgow	Lanarkshire	Awaiting Link
Wolfe Solutions	Tywyn	Gwynedd	Awaiting Link
Rogue State Media	London	London	www.roguestatemedia.co.uk
Callen-Lenz	Salisbury	Wiltshire	www.callenlenz.com
Dependable Productions	Borrowby	West Yorkshire	www.dependableproductions.tv
Arc Video	South Godstone	Surrey	www.arcvideo.co.uk
Cambridge UAV	St Ives	Cambridgeshire	www.cambridgeuav.co.uk
Vulcan UAV Ltd	Drybrook	Gloucestershire	www.vulcanuav.co.uk
AerialVue Ltd	Southport	Merseyside	www.aerialvue.co.uk
Trigger Image Ltd	Eye	Suffolk	www.triggerair.com
Coptercraft	Burghfield Common	Berkshire	www.coptercraft.com
Kingfisher APS	Croydon	Surrey	www.kingfisheraps.co.uk
University of Manchester	Manchester	Lancashire	www.manchester.ac.uk
AV8 UAS Soluitions	Christchurch	Dorset	www.av8uas.co.uk
Production Gear Ltd	Borehamwood	Hertfordshire	www.videogear.co.uk
Phoenix UAV Centre	Norton Saint Philip	Somerset	www.phoenixuavcentre.co.uk
BBStratus Ltd	Middleton Tyas	North Yorkshire	www.bbstratus.com
Horizon AP	Alnwick	Northumberland	www.horizonap.com
Shooting High	Stanton St. Quintin	Wiltshire	www.shootinghigh.co.uk
Reeder	Kessingland	Suffolk	Awaiting Link
Airstoc	Sheffield	South Yorkshire	www.airstoc.com

Organisation	Town	County	Website
Flyonix	Hatherleigh	Devon	www.flyonix.co.uk
TSO Imaging Ltd	Porthleven	Cornwall	www.tsoimaging.com
Skyhawk AP	Colwyn Bay	Wales	www.skyhawkap.co.uk
Hexcam	Norwich	Norfolk	www.hexcam.co.uk
AOS Group	Cambridge	Cambridgshire	http://www.aosgrp.co.uk
Access UAV Ltd	Coventry	Warwickshire	http://www.accessuav.co.uk
HeliDrone Surveys Ltd	Thaxted	Essex	http://www.helidronesurveys.co.uk
Aerialworx UK Ltd	Burnley	Lancashire	http://www.aerialworx.co.uk
Sky View Video	Balloch near Loch Lomond	Scotland	www.skyviewvideo.co.uk
Ronas Media Ltd	Shetland	Scotland	http://www.ronasmedia.co.uk
Coastway Ltd	Naas	Co Kildare	www.coa