

**Testing UAV-based Remote Sensing for  
Monitoring Well Pad Recovery**

**UAV Field Performance  
2014 Summary Report**

Prepared for the  
Alberta Biodiversity Monitoring Institute

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# Introduction

In the summer of 2014 the University of Alberta Applied Conservation Ecology Lab participated in a joint project with the Alberta Biodiversity Monitoring Institute (ABMI) and researchers from the University of Calgary to explore the potential of Unmanned Aerial Vehicles (UAVs) and aerial photogrammetry as a tool for the rapid assessment and monitoring of abandoned and reclaimed well pads.

The use of UAVs has become an increasingly popular technique in remote sensing and environmental surveying due to their ability to rapidly and inexpensively characterize large areas of habitat in a short period of time and on demand of the user. Aerial imagery captured by UAVs can be processed using specialized computer photogrammetry software to generate colour point clouds and terrain models of intricate resolution and complexity, potentially superseding the remote sensing capabilities of conventional Light Detection And Ranging (LIDAR) surveys at a fraction of the cost. However, due to its novelty, equipment, protocols and workflows suitable or optimized for the needs of projects such as ABMI's well pad recovery monitoring do not exist. The purpose of this collaborative project was thus to conduct a series of pilot trials in 2014 in order to test the feasibility of such an application, and to provide the needed information and understanding to develop necessary protocols. The project took place in two stages.

## *Stage I: Initial Flight Trials*

In the Spring of 2014, flight trials were conducted in the University of Alberta Rangelands Research Institute Mattheis Ranch in Southern Alberta and Beaver Mines in the Alberta Rocky Mountain foothills to examine: (1) the capabilities and limitations of several different classes and models of UAVs, and (2) the optimal time of day and meteorological conditions for surveys.

Specifically, ACE Lab supplied and tested a small UAV, the DJI Phantom quadcopter, for this comparative exercise. We also tested the use of Ground Control Points using a high-accuracy GPS receiver. Additionally, we developed a basic workflow for photogrammetry processing and shared this with our collaborators, especially the ABMI Geospatial Centre, which will be conducting the analyses using photographic data from future missions, including comparing its effectiveness with LIDAR as an aerial survey technique.

## *Stage II: Well Pad Survey Trials*

In the Summer of 2014, we reviewed the performance of our UAV and methods in Stage I and constructed a new, more capable UAV with insights gathered from initial flight trials. This new, custom-built UAV was then used to survey pre-selected decommissioned well pads currently monitored by ABMI. The objectives of this stage were to (1) refine UAV capabilities and protocols to the range of actual survey site conditions (2) test the feasibility and effectiveness of the UAV for aerial surveys at these actual sites.

Data was shared with the ABMI Geospatial Centre for analyses, and to use as a base on which to test and refine photogrammetry processing methods as well as assess its potential role in well pad recovery monitoring.

## Stage I: Initial Flight Trails

### *Flight Trial Areas*

Flight Trails were conducted at the University of Alberta (UA) Rangelands Research Institute (RRI) Mattheis Ranch, a 12,300 acre UA-owned research landscape 150km east of Calgary (Fig. 1). The flight trail site consisted of approximately 16 ha (400m x 400m) of open, rolling hilly terrain (Fig. 2) primarily vegetated by mixedgrass prairie at the approximate coordinates N 50.8756° W 111.8771°. This site was meant to represent simpler, open terrain. Flights were conducted between the dates of 15 to 17 June 2014.

Flight Trails were also conducted at a private property located just outside the town of Beaver Mines, Alberta in the Rocky Mountain Foothills. This site was meant to present more complex terrain, including large elevation gradients and forested areas (Fig. 3). The flight trail site was approximately 9 ha (300m x 300m) and consisted of a partially forested river valley slope ranging from 1315 m to 1345 m in elevation at coordinates N 49.4334° W 114.2222°. Flights were conducted between the dates of 18 to 20 June 2014.

### *Ground Control*

At both trail sites, forty Ground Control Points (GCPs) were laid evenly out across the 16 hectare plots using overturned buckets with numbers written in permanent marker on their exposed base. Each GCP had its centre coordinates recorded to a precision averaging approximately  $\pm 30$  cm using a Geneq iSXBlue II GPS.

### *UAV Flight Systems*

Three UAVs were present at the trails, one large fixed-wing and two multi-rotor units (Table 1; Fig. 4). The UAV we flew was the DJI Phantom quadcopter (Fig. 5), an off-the-shelf ready-to-fly (RTF) consumer quadcopter representing the smallest, lightest, most economic end of the spectrum of equipment present. The specifications of the unit are highly limited, with no autonomous capability, an endurance of approximately seven minutes, and the most compact camera of the three units tested.

Table 1. Specifications of UAVs trialed in spring and summer 2014.

UAV Make				
Model	QuestUAV QPod Slim 200	Mikrokopter Hexakopter XL	DJI Phantom	Prototype
Type	Fixed-wing	Multi-rotor, Hexacopter	Multi-rotor, Quadcopter	Multi-rotor, Quadcopter
Class	Commercial RTF	Commercial RTF	Consumer RTF	Custom-build
Pilot	Greg McDermid (UC)	Allison (UC)	Tobias Tan (UA)	Tobias Tan (UA)
Specifications				
Size	148 cm (w) x 65 cm (l)	102 cm (l) x 102 cm (w)	35 cm (l) x 35 cm (w)	45 cm (l) x 45 cm (h)
Weight	3.8 kg	2.7 kg	1.1 kg	1.5 kg
Max Speed	64 km/h	22 km/h	36 km/h	Not tested.
Endurance	40 mins	25 mins	8 mins	15 mins
Piloting				
Autonomy	Waypoint Programming	Waypoint Programming	None; Manual RC	Waypoint Programming
Guidance	Computer Telemetry	Computer Telemetry	LOS, FPV	Computer Telemetry
Launch Method	Slingshot	Vertical Take-off, Auto	Vertical Take-off, RC	Vertical Take-off, RC
Camera Payload				
Model	Sony NEX-7	Panasonic Lumix GX1	GoPro Hero 3 Black	Ricoh GR
Resolution	24 mp	16 mp	12 mp	16 mp
Sensor Size	23.4 × 15.6mm	18 mm × 13.5 mm	5.75 x 4.28 mm	23.7 x 15.7 mm
Weight	630g	420g	75g	243g
Resource Cost				
Min. Crew	2	1	1	1
Approx. UAV Cost	> \$10,000	\$6,000	\$2,000	\$3,000
Approx. Camera Cost	\$1,100	\$600	\$400	\$600

### Acronyms

RC - Remote Control

mp - Megapixel

RTF - Ready-to-Fly, a UAV which comes completely assembled and calibrated, and ready for take-off out of the box.

LOS - Line-Of-Sight, an aviation restriction where the pilot must be able to see the craft at all times.

FPV - First-Person-View, a mode of piloting using remote video transmitted from the craft to navigate.

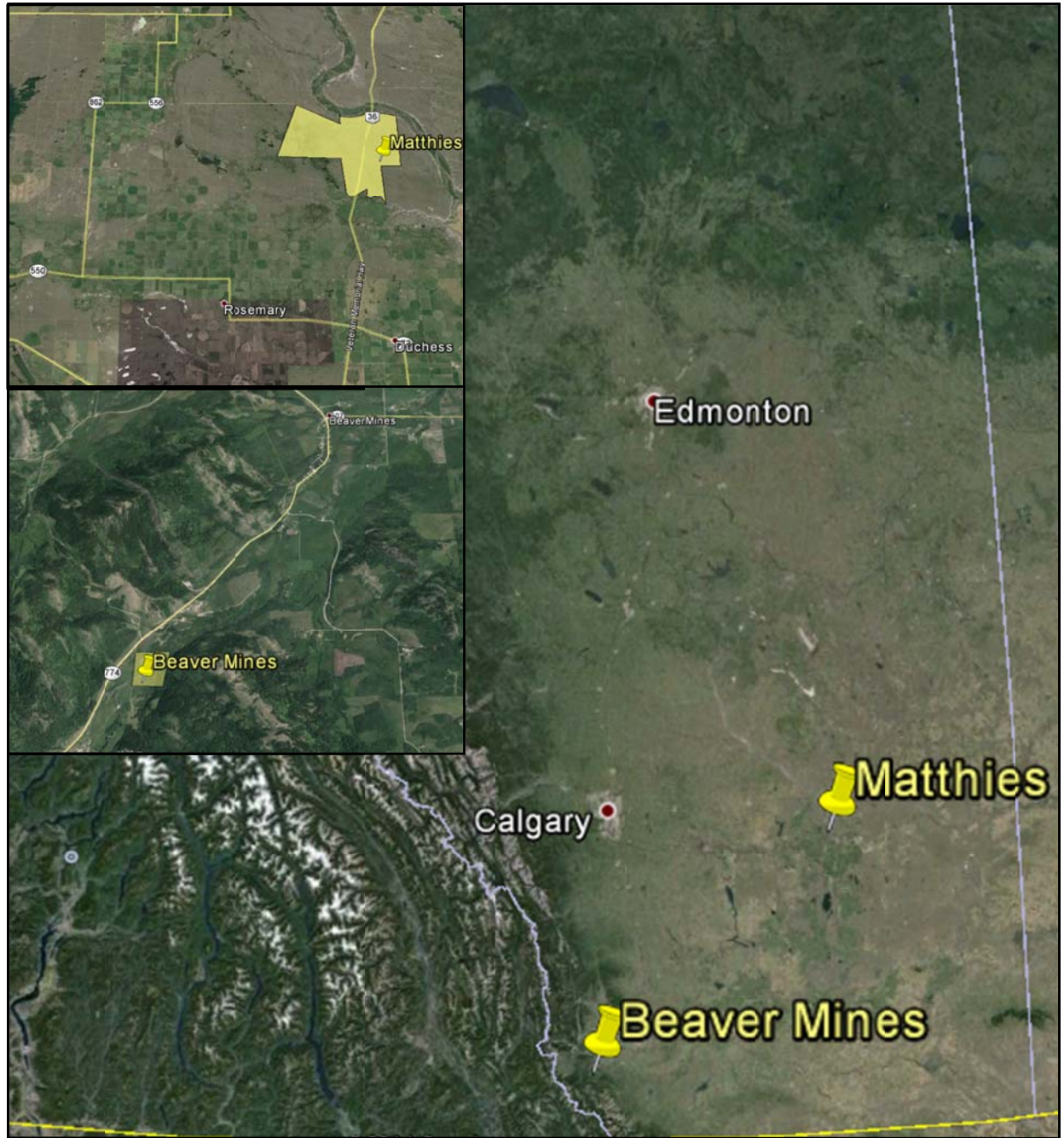


Figure 1. Map of Alberta showing locations of the RRI Matthies Ranch site (upper inset) and the Beaver Mines site (lower inset).



Figure 2. The RRI Mattheis Ranch landscape site consists of rolling hills of open dry mixedgrass vegetation. This aerial photograph was taken with a UAV hovering above plot centre; the base station can be seen in the distance and is located just outside the 16 ha trial survey plot. A red and a yellow GCP are visible in the foreground (circled).



Figure 3. The Beaver Mines site in the Rocky Mountain foothills consists of a river valley floodplain and adjacent slope. The red mark indicates the approximate location of plot centre while the clearing and open slope to the left-middle of the picture is included in the plot.





Figure 4. The three UAVs tested in Stage I. From left to right: The DJI Phantom quadcopter atop the toolkit, the fixed-wing Quest UAV on its stand, and the Mikrokopter hexacopter. The DJI Phantom's GoPro and Mikrokopter's Lumix G1 cameras are visible mounted on their gimbals.

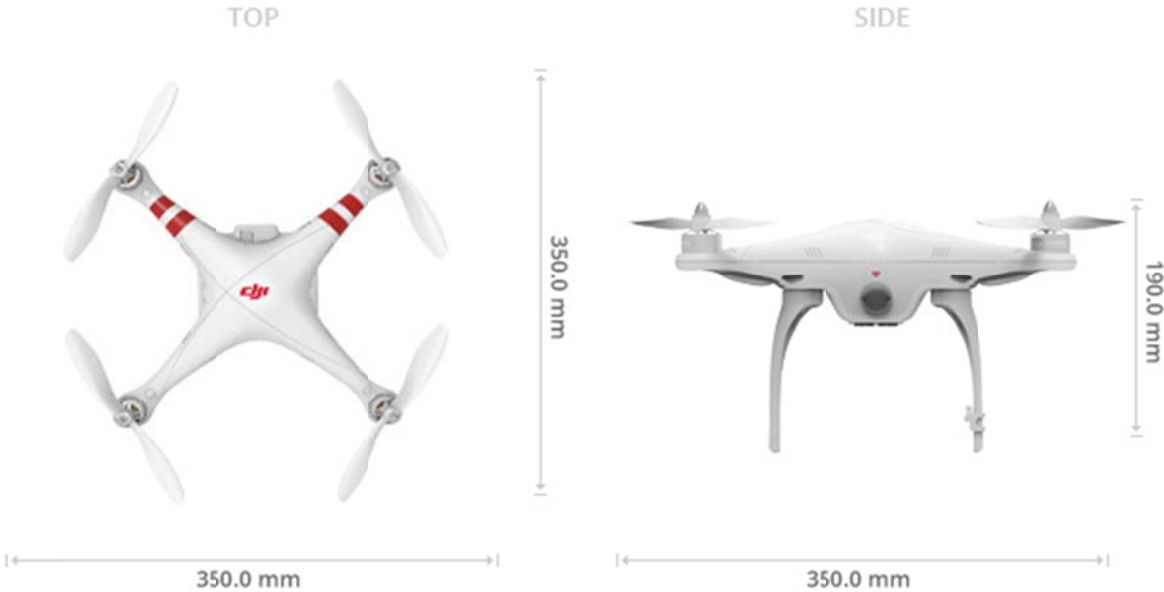


Figure 5. Top and side view of the DJI Phantom respectively in stock configuration without a gimbal or camera mounted.

## **DJI Phantom Flight Trial**

Weather during the trial period was inclement, consisting of light to heavy rain interspersed with drier periods of partly cloudy to overcast conditions. Wind was strong, with averages between 20 km/h and 30 km/h, with gusts to 50 km/h. The combination of high winds and precipitation resulted in very short and infrequent flight testing windows at both RRI and Beaver Mines. As only one UAV could be airborne at any one time in a given window and pre-flighting larger UAVs took significant amounts of time, the number of flights conducted by each UAV was small. For the DJI Phantom, a total of seven flights consisting of three test flights and four survey missions were conducted at RRI, and a total of five flights consisting of three test flights and two survey missions were conducted at Beaver Mines.

It became obvious on reaching the site and laying out ground control markers that the full 16 ha survey plot at RRI was beyond the endurance capabilities of the DJI Phantom. A 4 ha quadrant of the 16 ha flight trail plot (200m x 200m) was chosen for flight trails with the phantom. The lack of autonomous capability and waypoint programming necessitated manual remote control piloting by Line-of-Sight (LOS) from the plot centre. As the horizontal distance and altitude of the UAV was difficult to gauge accurately by eye beyond 40m out, the flight path of the UAV was additionally guided by colleagues standing at the plot boundaries and updating the pilot of the UAV's position via two-way radio. A lawnmower flight pattern was flown to ensure roughly even coverage and overlap, with the camera set to take two pictures per second.

Not possessing autonomous capability, there is no significant pre-flight planning and waypoint programming to conduct for the DJI Phantom. Some site reconnaissance is advised, including checking wind conditions. The craft is extreme portable, fitting in a large hand-carry pelican case along with all necessary accessories and spare parts. Before flights, the 2200 mah flight batteries should be charged and the 4x AA remote control batteries checked for adequate charge. The GoPro camera should also be charged by USB cable and the micro-SD storage card emptied. The on-board video transmitter should be disabled to reduce battery consumption.

Deploying the Phantom is the easiest of all UAVs in this report: The carry-case with the phantom is carried out to a chosen launch location, the phantom, remote control, and a battery is removed, and the phantom set atop the case. Upon inserting and connecting the battery, the unit powers up and runs through an automated pre-flight check. After a minute for GPS acquisition, an indicator light will notify the pilot that the unit is ready for takeoff, upon which the motors are armed. Given an appropriate window in the wind for the safest takeoff, the pilot opens the throttle for the UAV to vertically ascend and begins a stopwatch to gauge how much flight time has elapsed and is remaining. Upon reaching target altitude, throttle is released. In calm air, the Phantom will maintain its horizontal and vertical position to within 0.5 m without needing pilot input.

After take-off, we flew the Phantom at maximum horizontal speed in a lawnmower pattern over the 4 ha subplot. The flight continued until the UAV had completed its pattern and reached the far corner boundary of the plot, or until 8 minutes had elapsed, after which we brought the UAV back to plot centre and landed it. The entire process from being cleared to deploy to packing up and returning took, on average, approximately twenty minutes.

## **Capabilities and Limitations**

The DJI Phantom was able to ascend to mission altitude and complete the four hectare survey missions with sufficient data and overlap for photogrammetric analysis. However, the flight height combined with the small and lesser capable camera made the GCPs indistinct on the imagery, which may pose problems with post-field processing. The Phantom may be needed to fly at a lower altitude for better resolution, but this trade-off with a decrease in camera field of view would increase the flight time required potentially beyond the capacity of the battery.

Aside from meteorological limitations, the chief disadvantage of the low-cost DJI Phantom was found to be the low battery life and lack of autonomous waypoint programming. Manual piloting by LOS from over 50 m away is difficult and requires the assistance of spotters on the ground crew, and the flight pattern was erratic and non-replicable. This poses potential problems in long-term monitoring where the survey protocol has to be replicated as closely as possible to the originating flight at each site.

The DJI Phantom quadcopter however had advantages over the other larger, more complex and more expensive UAVs flown at the trail. Aside from its low cost and ease of replacement, it is fairly hassle- and maintenance- free, and highly portable. This is noted in the field to strongly contrast with the other two UAVs, which required significant set-up preparation time and large amounts of equipment and maintenance in the field. The DJI Phantom and similar consumer UAVs require no additional computer equipment, tripod, stand or aerial. Lastly, it is able to transmit back first-person video from the GoPro camera on board to a set of LCD goggles worn by the pilot. For this reason the DJI Phantom excels at scouting surveys and quick, one-time surveys of smaller plots (<1 ha), as opposed to long-term monitoring of large plots.

It was also noted that the high maneuverability of the multi-rotor units is almost a requirement for forested areas as larger fixed-wings required significant clear space and preparation for effective take-off and landing. Given the additional set-up time needed, fixed-wings may be suited to survey larger areas (>20 ha) or remote plots (>100m from nearest clearing) but are highly inappropriate for monitoring single, smaller plots (<4 ha). The latter is more resource-effectively accomplished using small multi-rotors with specifications meeting the

requirements of the mission. It is clear that current multi-rotor UAV capabilities, which exists in a wide range and scales with costs, are perfectly capable of well pad monitoring surveys. The challenge is in finding the right UAV to fit the niche in terms of ease of use and cost-effectiveness.

## **Optimal Meteorological Conditions**

The optimal conditions for UAV-based aerial photogrammetry revolve around two sets of factors: (1) conditions suitable for safe flight of the UAV and (2) conditions suitable for producing photography usable in photogrammetry and analyses.

As a form of aviation, UAV flights are highly dependent on meteorological conditions. It was determined that the DJI Phantom is not safe to fly in winds of over 15 km/h, whether steady or gusting. The phantom itself exhibits excellent self-stabilization and can handle flying in strong winds. However, wind gusts may knock it off course or orientation, causing piloting difficulties, and sustained winds greater than its maximum airspeed may move the unit away beyond visual range and render it unable to return. Strong headwinds also greatly reduce the ground speed of the unit, causing the mission to take longer to complete and possibly reaching the endurance limit of the battery and causing a failsafe abort.

Additionally, precipitation of any kind is mission-prohibitive. Aside from personnel safety issues in a risk of lightning, the UAV can fly in light rain if all ventilation ports are covered. However, the long-term effect of exposure of the motors to rain and the shutting off of air cooling is not known. Another issue lies in the payload gimbal and camera, which are mounted beneath the unit but still exposed. These are not waterproof and exhibited erratic behaviour in light rain including glitching and freezing up, preventing successful imaging surveys. Cloud cover however does not affect GPS acquisition and position stabilization.

Temperature is a factor known to degrade electronic and battery performance at both upper and lower extremes. While the UAV operating temperature is specified by the manufacturer at -10 to 40 °C, the extremes should be avoided; when approaching freezing, the lithium-polymer batteries required by UAVs cease to perform as expected. Additionally, high ambient temperatures may post difficulties for power equipment such as speed controllers and motors to cool adequately, resulting in reduced performance and the possibility of a failure related to overheating.

The conditions for producing optimal photography are generally understood to relate to having good light levels for photography, and having spatially and temporally uniform light levels for generating point clouds which spectral analyses are to be conducted. Low light

conditions, such as during overcast periods, produced "muddy" and low-contrast imagery. It is estimated that a cloud cover of less than 50% is needed for the less sensitive GoPro Hero 3 camera. A second concern is the presence of shadows cast by trees and other tall objects when the sun is closer to the horizon, or even clouds which may shade some periods of the. Although the photogrammetry software is not limited by this so long as shaded portions have adequate definition, the presence of sun-lit and shadowed patches would artificially introduce micro-site heterogeneity in a spectral-based analysis. For comparisons between sensor platforms and light levels, UAV data from the various trails were conveyed to the ABMI Geospatial Centre for aggregation and examination with University of Calgary UAV data.

## **Recommendations**

### *Flight System*

Drawing upon the experiences of the other multi-rotor UAV flights and discussions, we have determined that, capabilities-wise the DJI phantom exists at the extreme low end of the scale and the Mikrocopter exists towards the middle-upper end. It must be noted that the Mikrocopter manufacturer provides poor support and specifically restricts its own software and hardware as a buyer lock-in strategy and charges exorbitant sums for removing each limitation in software similar to the way software trails lock features until an activation code signifying a purchase is input. We strongly recommend that such UAV manufacturers be avoided.

A UAV with the necessary capabilities would fall towards the middle of the range, and may become increasingly inexpensive and user-friendly as UAV technology moves into mass production for the consumer market. During the project, custom-building a UAV from off-the-shelf, modular parts was an attractive option; one of the advantages of this approach was an intimate understanding of the function of a UAV and an ability to repair minor damages rapidly in-house without the delays and high prices associated with returning a UAV to a vendor for servicing. However, regardless of make or model, it was determined that a multi-rotor UAV surveying an approximately 4 ha plot should be, at minimum, capable of:

- (1) At least 10 minutes of flight time, including accounting for the energetically costly ascent to mission altitude.
- (2) Autonomous, waypoint-directed flight
- (3) Real-time telemetry and location feedback to a ground station.
- (4) A payload of a higher-grade compact with a large sensor size, optimally 16 megapixels or higher.
- (5) Deployment without the need for a large amount of setup time, and be operable by technicians without the need for intensive training or a steep familiarization curve.

## *Mission Planning & Scheduling*

Beyond the UAV system itself, proper planning and scheduling of survey flight missions is critical for success. The primacy of considering meteorological conditions in scheduling flight missions both at a date and time level requires the pilot to be familiar with weather patterns and predictions. As part of a standard operating protocol required by Transport Canada for UAV operations, hard limitations outside which a UAV mission must be aborted and the UAV grounded must be set according to the capabilities of the hardware, pilot, and environmental safety factors. For these, it is recommended that the bounds of multi-rotor UAV operation include the following as flight prerequisites:

- (1) No precipitation is expected or imminent
- (2) Winds are consistently under 15 km/h steady and 20 km/h gusts
- (3) It is daytime, between half an hour after sunrise to half an hour before sunset
- (4) Ambient air temperature is 5 – 35 °C.

It is important for the pilot to be given control of the mission to determine whether conditions are optimal, from guidelines, knowledge and experience. As caving to pressure to complete a mission despite suboptimal conditions may result in equipment damage, pilots should be conservative in making decisions for whether to fly. Establishing a rigid schedule is not likely to have good results; instead, a UAV survey crew needs to be flexible, highly cognizant of weather variables, and pay close attention to them during the flying season. It is recommended to have a spreadsheet calendar indicating such factors as probability of precipitation, forecasted wind variables, and other considerations such as pressure systems and fronts to present an overview of conditions which might promote or prohibit flight missions at target sites. Such a spreadsheet could be hosted on Google Apps for sharing with team members and planning logistics.

Wind speeds are lowest at dawn and dusk, and strongest and most turbulent from noon to afternoon. It is thus recommended from a flight systems point of view to conduct UAV missions in the morning, and in the evening after winds have died down, and never in the mid afternoon when thermal and wind activity are strongest, except in the presence of a uniformly calm day such as those brought about by high pressure weather systems. However, if spectral analysis of the point cloud is an objective, the window is further reduced to the period during which the sun angle does not cast excessive shadowing in the surveyed plot - approximately halfway between sunrise and noon. Late afternoon weather is more variable and a time window cannot be specified; instead field conditions must be monitored as they develop.

### *Supporting Equipment*

Other smaller considerations included the need for a portable launch platform, as the height and bumpiness of natural vegetation was an issue at take-off and landing. The presence of a colour balance reference diagram on the launch platform may be synergistic, allowing UAV cameras to capture colour-calibration information at takeoff.

Having an instrument in the field reporting wind speed, including current speed, average speed, and maximum gust, is a necessity.

The need for portable power for powering electronics and recharging batteries cannot be overstated. This can be achieved with a portable generator, or a vehicle-based power inverter. It is however recommended that vehicle-based systems be designed and installed by professionals as inappropriate equipment, lower-grade equipment or thinner wiring may be a significant fire hazard. Lithium batteries should also be stored in fire-retardant pouches during charging and for transport.

## **Stage II: Well Pad Survey Trials**

### **Developing Purpose-built Prototype Multi-rotor Monitoring Survey UAV**

The objective of accomplishing well pad surveys in the boreal and foothills regions presented a new challenge over the initial exploratory flights of Stage I. The closed-in, forested environment prevented the use of fix-wing aircraft, the larger autonomous multi-rotor was unavailable, and in our examination of fit-for-purpose, DJI Phantom quadcopter did not possess the required capabilities. In order to meet this objective, a new prototype UAV was designed and purpose-built to have the capabilities specified, including longer flight time, full autonomy, and payload capacity for a more capable camera (Table 1). Having a platform already in the works since May with parts ordered and arriving, system development and flight testing immediately began on returning from Beaver Mines in June, and continued over the month of July 2014 in preparation for wellpad survey missions.

#### *System Design*

The UA ACE Lab collaborated with the UA Department of Biological Sciences Fabrication Workshop in the engineering of components for the prototype UAV (Fig. 6). Components were designed in Adobe Illustrator and laser-cut or machined; G10 fibreglass composite formed the base and structure of the craft, with standard acrylic plastic used in the electronics and payload mounts. The flight computer used was the 3D Robotics APM 2.6, a proven and well-supported system used in many consumer and hobby UAVs. Stabilization and navigation were provided via on-board sensors including a gyroscope, accelerometer, tri-axis compass, barometric altimeter, and GPS receiver. Propulsion was provided by four T-Motor MS2216-11 900KV motors with 10/5 inch diameter/pitch carbon composite propellers; these were in turn powered by a 5000mah 30C 11.1v lithium-polymer battery back via a power distribution frame and four 30A DYS Electronic Speed Controllers.

Control and telemetry were provided via a 2.4ghz remote control receiver bound to a FrSky Taranis controller/transmitter, as well as a 3D Robotics 900mhz digital transceiver. The latter was paired with an identical transceiver at the ground station, connected via USB to a Windows 7 laptop running the open-source APM Planner v2.0 flight software. The software provides accurate realtime readouts of the UAV's status, heading and position on cached google maps imagery, as well as allows waypoint-based autopilot programming. Red and white LED strips were added to the front and rear of the UAV respectively to indicate forward facing direction from a distance.



### *Flight Testing*

The prototype UAV achieved its maiden flight by manual remote control on July 4 at a testing field on the University of Alberta North Campus. Significant amounts of calibration and further refinements were necessary before achieving the target endurance level. However, when payloads were added, flight characteristics suffered. UAV weight had to be reduced by experimenting further with different materials and measures, including switching to a stainless steel payload mount, switching to wooden shock-absorbing landing gear, and acquiring lighter batteries. A protocol to balance and secure propellers was also developed after an accident in which a propeller vibrated loose in midair, causing a crash that did not cause any damage beyond snapped landing gear. A large amount of landing gear struts were fabricated for easy and convenient replacement in the field, so this was not an issue. On July 20, a successful mission on full autopilot was flown around the test field in a lawnmower pattern at 20 m altitude, including a fully autonomous landing.

### *Flight Parameters*

The camera chosen as the well pad survey prototype UAV's optical sensor payload was the Ricoh GR camera, an extremely light 16 megapixel APS-C camera with a built-in intervalometer (Table 1), with the Canon Ixus 220 used on another fixed-wing UAV at our lab, the Sensefly, as a backup. Mathematical algorithms were developed to determine the altitude at which UAVs must fly for a certain pixel size, the exact dimensions of the land area covered by an aerial photo from that altitude, and the various characteristics of the lawnmower flight pattern used, including flight segment count, spacing, length and position, for a specified overlap and target survey area. These algorithms are specifically calibrated to each candidate camera. It should be noted that the determinant of flight paths and patterns are thus not the UAV, but the camera. However, commercial UAVs may have integrated, unchangeable cameras for which they have developed software assisting the pilot in computing UAV flight paths.

Flight plans and mission parameters were developed with the objective of yielding a 2cm/pixel resolution of a 4 ha plot (200m x 200m) with >70% overlap. Flight trials with full payload and mission parameters were conducted at the University of Alberta South Campus, initially unsuccessfully, and the flight plans and parameters were refined iteratively. The final flight plan proven with repeated testing success consisted of two flights for each survey mission (Fig. 7) to allow significant safety room in battery lifespan in case of adverse an emergency. The flight pattern for each UAV mission was approximately 2.3 km long, flown at up to 25 km/h and captured aerial imagery at a rate of one per second.



Figure 6. Photograph of prototype UAV in the field preparing to undergo a trial flight. The blue objects are the 5 Ah lithium-polymer batteries. The camera has been removed for arming.

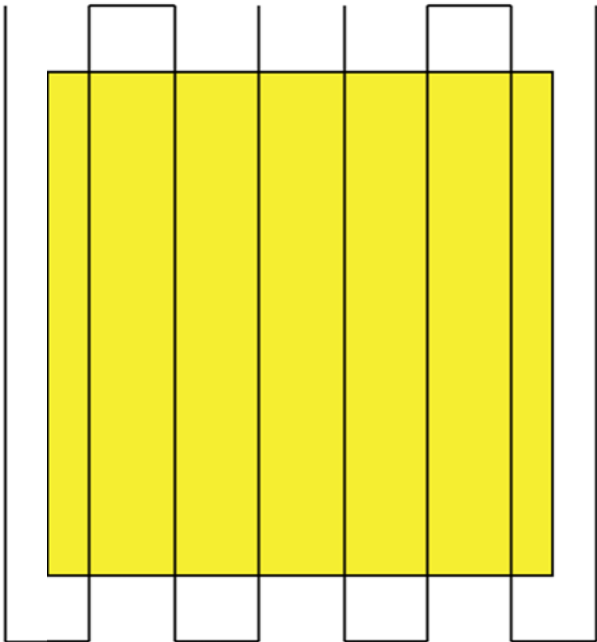


Figure 7. Mission flight pattern for the prototype UAV mounted with a Ricoh GR camera flying at 76 m altitude to produce 2 cm pixel size imagery of a 4 ha plot with 70% overlap.

## Well Pad Monitoring Plot Survey Flights

### *Study Areas & Protocol*

Candidate well pad monitoring sites for initial test survey missions were identified and prioritized from a pool of recently surveyed sites in Northern Alberta provided by Anne McIntosh. The pool of test sites were grouped into Whitecourt and Slave Lake geographic localities and weather forecasts for both areas were tracked and updated daily. Sites were prioritized based on accessibility to allow the truck to be used initially as a base station. Based on weather windows and a conservative rate of one mission per day, the objective of the field session was to survey a minimum of four well pad monitoring sites per locality: two foothills and two boreal.

Between the dates of 28 and 31 July 2014, UAV field trials using the lab-developed autonomous quadcopter were conducted at four selected sites (Table 2, Fig. 8) in the Slave Lake region, accomplishing the objective successfully. Upon reaching each site, two technicians laid out Ground Control Points consisting of ten upturned red flower pots painted with bold white roman numerals while a third, the pilot, set up the ground station, conducted pre-flight checks, and programmed the mission waypoints into the UAV from a laptop. The GCPs had their locations recorded by the iSxBlue II survey-grade GPS unit, while technicians navigated using a Garmin GPSMap 62sc GPS unit and kept in contact with radios.

When GCP distribution was completed, the assisting technicians were repositioned around the site to act as spotters and track and report on the progress of the UAV, especially in case it leaves the visual range of the pilot. The telemetry connection reporting UAV status and position was also intact at all times. When a window of calmness was present, the camera and UAV were armed and the UAV was launched, ascending to a sufficient height to clear trees before the autopilot was activated. The UAV would then climb to the target altitude before beginning the lawnmower pattern on autopilot. At the end of its programmed flight path, the UAV returned to hover above the launch site for the pilot to manually land the craft as automated landings were not reliable in densely forested areas.

### *Flight Missions*

Of a total of eleven pre-selected potential target sites in the Slave Lake Area, five were dropped due to access difficulties or lack of a clearing for launch. It may be necessary to use a larger fixed-wing UAV to survey these, launched from a clearing some distance away. Of the remaining six, the four best sites were visited and surveyed in turn. One site was successfully surveyed in the evening of 28 June in clear and low wind conditions, and two sites on the

morning of 29 June in clear and calm wind conditions. Missions were completed successfully with some rough landings due to wind and thermal activity. The 29 June morning flight was executed perfectly with optimal UAV performance due to “glassy” calm conditions.

The field crew departed to conduct the fourth survey in the late afternoon of 29 June, with the intention of departing the following day for Whitecourt as the window of calm weather in central Alberta was closing. However, while the UAV was airborne and about to return home at the end of the final mission, the UAV descended under power and crashed in the forest from 76 metres altitude, at the edge of the well pad cutblock.

### *Post-flight Assessment*

The data uplink was intact throughout the entire descent and crash, showing the UAV maintaining level orientation and with propellers at maximum output during the descent into the tree canopy, before one or more propellers struck tree branches and the UAV lost control. After observing the sequence of events visually and on computer telemetry, the UAV was instructed to disarm if it hadn't automatically done so, and its precise GPS coordinates were recorded and input into the crew's GPS units. Due to difficult terrain and dense brush it took a while to reach the crash location and a short while more to locate the UAV.

The UAV was recovered with its fibreglass composite frame, electronics and camera intact thanks to a "roll cage" design, but the acrylic electronics mounts and metal payload mount, having absorbed the forces of impact, sustained damage warranting replacement. All propellers and landing gear were also significantly damaged and needed to be replaced. Additionally, after sustaining a crash, the condition of the motors may be suspect and will need to be tested before flying again. The electronic speed controllers may also need to be replaced due to the chance of burning out due to sudden opposing forces on the propellers during the crash. The lithium battery was highly deformed as the "roll cage" and its metal mount had twisted from the forced of impact; however, it was, extremely fortunately, not breached, and was safely contained in a fireproof bag within a sealed pelican case and later disposed of by campus hazardous waste management. The camera was still collecting imagery with lens extended when the UAV was recovered.

An analysis of the crash indicates that the likely cause was wind turbulence, most probably a wind rotor. A rotor is a strong downward cycling air pattern that occurs downwind from a tall obstruction, somewhat similar to a waterfall as wind spills over the side of a building, mountain, or in this case, a sudden drop from the edge of a 30-40m tall tree canopy. Winds had picked up noticeable toward the end of the flight and were gusting at roughly 25 km/h, above the

safe zone identified earlier in this report, but the flight was not aborted as it was nearing completion and the crash occurred as it was making its way back to launch.

Mechanical and electronic failure can be ruled out from the flight debugging logs collected during the time the UAV began descending until its crash; while the UAV was descending, it was maintaining level, indicating avionics were functioning normally, all motors and propellers were functional and the craft was stable; thrust was at maximum and the telemetry altitude readings matched the visual descent, indicating the UAV was aware of its downward movement and attempting to compensate. However, full thrust, usually capable of ascending at 1-2 m/s with full payload, was insufficient to maintain altitude. This indicates that the mass of air the UAV was in was descending at a rate greater than its maximum climb rate. At the point of contact with trees, the UAV would have been knocked out of level and its propellers would have shattered against thicker branches, making a crash inevitable.

Data from the flight was recovered, concluding the field session objectives for the Slave Lake locality. However, due to the need for ordering a full set of propulsion components for repairs (there were not enough spares for a complete rebuild) and the onset of inclement weather, the UAV missions scheduled for Whitecourt were suspended for the season. Photograph and GCP data from the surveys was sent to the ABMI Geospatial Centre for photogrammetric processing and a detailed assessment of the seasons' quadcopter UAV trials were undertaken.

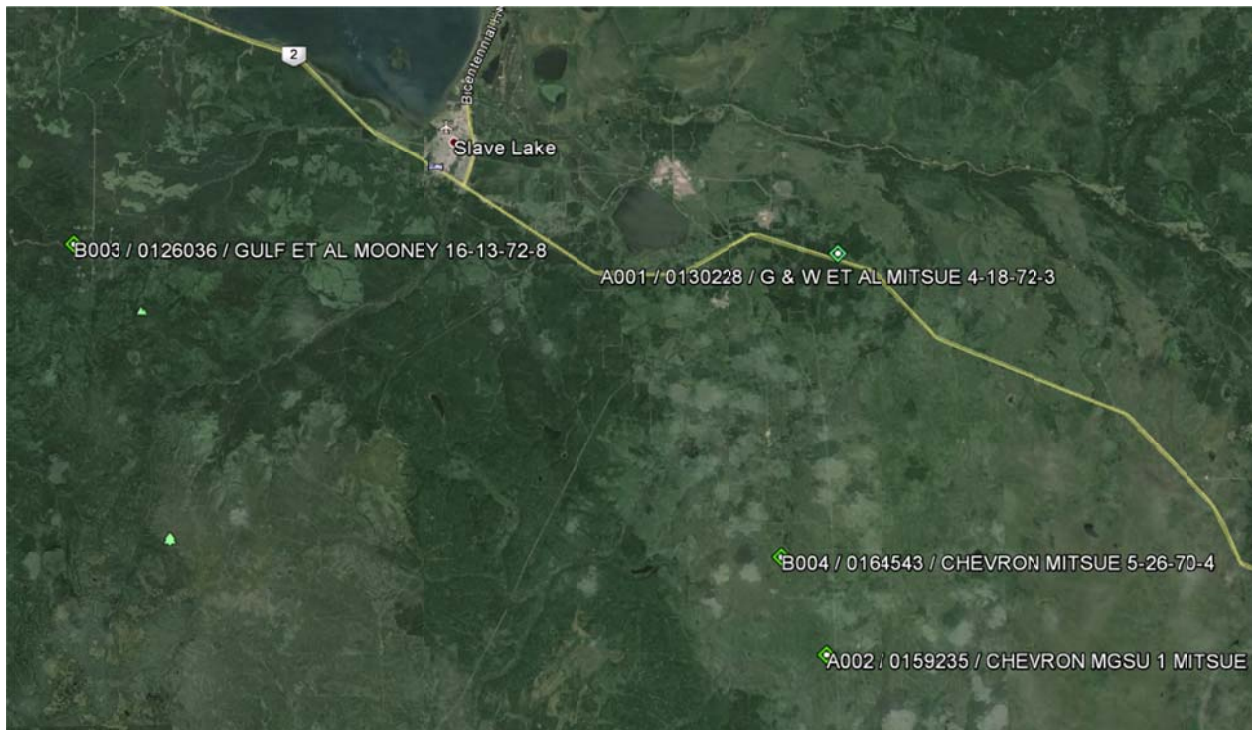


Figure 8. Map of well map monitoring sites at which UAV survey missions were flown in the locality of Slave Lake.

Table 2. Candidate and chosen sites for UAV trials. X under Mission ID indicates sites that turned out to be inaccessible while blanks indicate backup sites that were not flown.

Mission ID	License No.	Access from truck	Wellsite Vegetation	Well name	ABMI ID	LAT	LON	Cert. Age	UAV Survey
01	0130228	On Road	Clear, Some Trees	G & W ET AL MITSUE 4-18-72-3	Boreal9	55.231466	-114.457654	22	Surveyed 2014-07-28 18:00
02	0149979	300m Truck Trail	Clear	CHEVRON MGSU 1 RH MITSUE 5-4-70-3	Boreal14	55.027004	-114.405432	18	Surveyed 2014-07-29 11:00
	0116946	On Road, longest drive	>50% Regrown, Many Trees	UNEX ET AL FAUSTS 11-11-72-11	Boreal16	55.224458	-115.583897	26	
X	0159235	Not Accessible - Sinkhole in Road	Clear, Some Trees	CHEVRON MGSU 1 MITSUE 6-12-70-4	Boreal13	55.043538	-114.472590	17	
X	0029673	800m Hike	Clear	HOME ET AL MITSUE 12-6-70-3	Boreal12	55.034253	-114.455318	18	
X	0154290	100m Hike	Clear	CHEVRON MGSU #1 MITSUE 7-34-71-4	Boreal10	55.189497	-114.522090	17	
03	0126036	On Road	Some shrubs, partial wetland	GULF ET AL MOONEY 16-13-72-8	Foot1	55.240166	-115.083775	14	Surveyed 2014-07-29 15:30 Half
04	0164543	On Road	Clear, Some Trees	CHEVRON MITSUE 5-26-70-4	Foot6	55.090006	-114.507769	14	Surveyed 2014-07-29 8:30
	0127930	100m Hike	>50% Small Trees	SASKOIL ET AL MITSUE 1-2-75-6	Foot7	55.456474	-114.818228	23	
X	0027489	Middle of Woods	Overgrown	IOE SYLVIA NORTH 4-10-75-6	Foot9	55.477367	-114.851854	48	
X	0100876	300m Hike on "Wet Goat Trail"	Indeterminate	SULPETRO ET AL WIDEWATER 7-8-73-7	Foot3	55.305515	-115.036269	29	

## **Recommendations**

### *Regulatory Approval*

The objective of obtaining a Special Flight Operations Certificate (SFOC) for this stage of the project was abandoned due to a prohibitive time horizon and procedure which would defeat its purpose. This may be borderline legal as non-commercial/research/educational UAV flights may be in a grey area between "recreation" and "commercial" use of UAVs. The field crew otherwise possessed all of the prerequisites, including a pilot with Model Aeronautics Association of Canada membership and recreational insurance coverage, UA liability insurance for commercial activity, and as a standard practice, field flight and safety protocols and contingency plans. All flights were conducted in uncontrolled airspace and remote wilderness areas with no ground or air traffic.

For the purposes of all future UAV initiatives, it is strongly recommended that plans be formulated well in advanced. For example, sites should be selected four months in advance at best, and broad SFOC applications submitted three months in advance, covering the entire flying season. This is necessary to be clearly within the legal framework as well as to establish a good record and rapport with Transport Canada in a way that may allow ABMI or ACE Lab UAV working groups to acquire an umbrella permit for future operations. There is no harm in acquiring a large number of broad SFOCs detailing potential plans, selecting sites closer to the season, and cancelling SFOCs that are not used.

### *Flight & Ground Crew*

A UAV field crew was determined to ideally consist of three people, consisting of a pilot/system maintainer and two field assistants. These assistants act as ground crew, laying out Ground Control Points before launch, and acting as spotters during the flight. Transport Canada regulations require a minimum of two crew members for UAV activities, while Field Safety Protocols also strongly recommend a buddy system of two technicians working in proximity to each other in the backcountry, especially in areas where bears are present. The pilot would remain at the ground station near the truck, and is fairly safe, but the technicians laying out the ground control or standing at distant clearings spotting for the pilot may require additional safety equipment such as bear spray. Having every crew member equipped with a radio is essential.

### *Ground Control Points*

Larger Ground Control Point markers with more obvious and distinct markings may be needed. However, the number of GCP markers required is unknown. Experiments should be conducted in which a large number of Ground Control Points are present, and then subsampled in post-processing, to determine the number and spread at which accuracy and precision declines. An optimal number of GCPs per unit area can then be written into future UAV protocols.

### *UAV Flight Performance, Design & Selection*

The learning experience from purpose-building the prototype, and subsequent crash, has highlighted several important points to consider. Perhaps the most direct is the danger of turbulence posed by tree canopies, and the specific danger of rotors at the edge of cutblocks, clearings and partial-regrowth wellpad sites and linear features. In recreational aviation, this is a fact well known and taught to pilots to avoid regardless of skill level. However, the need to survey precisely these areas thus requires the adoption of several guidelines, including:

- (1) Minimal clearance over tree canopies. General forest height should be taken into consideration when designing the flight pattern in the field.
- (2) Conservative avoidance of the potential for adverse wind conditions. Flying in the afternoon is more risky than in the morning due to variable wind and albeit weakening, wind conditions. As a best practise, only one flight should be scheduled per day, during the calmest part of the day in the morning. Notwithstanding that, in general field activities should begin as early in the day as possible and concluded by noon; the rest of the day should be spent on data post-processing, maintenance, scouting and possibly GCP-laying and flight-programming the next day's site.
- (3) UAV propulsion and power systems should have adequate headroom for thrust and stabilization in suboptimal conditions given their payloads. Operating UAVs at the edges of their optimal flight characteristics, as the prototype may have been due to rushed development for deployment, should be avoided.
- (4) UAVs should have good telemetry downlink and control software, such as in the case of our prototype, so that even in the event of a failure and crash in the forest, recovering the UAV and data is made easier.



All UAVs are exposed to conditions which may be unexpected and adverse. UAVs are always subject to the chance of damage and loss every flight. This must be taken into cost-benefit assessments, logistics, and field planning. For example, for any long term commitment to a use of UAVs, it may be necessary to have a standard fleet of several of the same unit, with many spare parts and backup units. The cost of wasted accommodations, man-hours, truck time and fuel from going out to a survey site and crashing a UAV may eclipse the actual cost of an additional UAV on standby; such a tool is thus more effective to multiply on a budget in the long run, rather than letting it be the single point of failure. Extremely expensive or overly complicated UAVs should also be avoided due to the universal chance of accident or failure, especially with crews of lesser experience. Consumer off-the-shelf UAVs that are easier to use, more tolerant of error, cheaper, and proven to be reliable from a large user base, are thus more viable than commercial-grade UAVs that require significant purchase costs and additional software and training. It is recommended to test consumer UAVs paired with survey-grade camera equipment for performance, endurance, and simplicity to identify a model and paired camera most cost-effective as well as field-resilient for monitoring needs.

Multi-rotor UAV selection should not focus on whether the UAV is marketed as having a certain payload range and a certain endurance; it must be understood that all factors interplay with each other and that increasing payload will decrease endurance and/or flight performance. In all cases, flight performance must be regarded as crucial and additional headroom in payload be allowed.

Building a purpose-specific UAV came with many advantages, including an intimate understanding of the system, its limitations, the ability to improve the system over time, the ability to repair it in-house without long wait times and high fees associated with dealer servicing, and the low cost of parts, initial assembly, and future replication. However, the learning curve was steep and there was a hidden investment required in the form of many hours of time spent flight-testing, troubleshooting and refining the system. Additionally, building an optimal UAV is an iterative approach, and it is certain this first prototype is hardly optimal flight-efficiency wise. Consumer and commercial UAVs, while at a higher cost for the necessary capabilities, have a significant degree of iterative R&D already invested in them to be as efficient as possible. If there are other choices, it is apparent that developing a custom UAV in-house is not the best option for a first-time UAV initiative more focused on results rather than engineering.

However, it may not be necessary to make six-digit investments for a capable multi-rotor UAV platform, thanks to emerging technologies and mass production of increasingly capable UAVs in the past year alone. With this in mind, ACE Lab is planning on acquiring next-generation, fully-assembled and ready-to-fly units for system characterization and flight trials in

2015. The cost is roughly equivalent to that of building a custom unit presently and forecast to fall gradually.

*Decouple UAV and Camera in Feasibility, Cost-benefit Assessment*

This field season, UAVs had generally been considered single units in combination with their payload camera. In the commercial UAV industry, this is the case as many cameras have to be custom-wired into the flight computer for shutter triggering, and the UAV itself may have been designed to accommodate that specific camera model. Cameras may even be fully integrated into and inseparable from the UAV. However, in the course of developing our UAV prototype, it was realized that this is a poor and unnecessarily inflexible assumption.

Camera systems and UAVs should be decoupled for selection and assessment in cost-effective system design. The entire purpose of the UAV was to function as a vehicle for the camera. Camera characteristics determine the output data quality, the flight path, the time and distance and pattern the UAV has to fly, and is the key component to examine and modify for the accuracy, precision and composition of the resulting point cloud. Any UAV that can carry the camera and fly the specified flight path with resilience to field conditions would suffice, while the cameras should be tested against each other for performance at difference heights, speeds and lighting conditions.

## Conclusion

From the many successful trials conducted, UAV-based remote sensing as a method for monitoring well pad recovery is determined to be feasible from a technical and field perspective. UAV technology has advanced in the interim, bringing autonomous, high-endurance UAVs to the consumer marketplace and negating the need for specialized commercial or lab-built aircraft. While many optimizations for cost-effectiveness and efficiency still need to be made, and a robust flight protocol developed, the focus should necessarily shift from the capabilities of the UAV platforms themselves to the need to substantiate the robustness of the workflows from camera to point cloud.

The next stage in developing a UAV-based monitoring initiative may lie in quantitative trials demonstrating the accuracy and precision of the outputs through surveys of known measurements and repeated flights under similar conditions. This is a vital foundation step in affirming that UAV-based monitoring is not only possible, it is reliable and useful. We propose in the coming year to take advantage of new platforms and building quantitative foundations to move forward with developing UAVs as a tool for monitoring the recovery of human disturbances such as well pads, and conservation and environmental monitoring as a whole.