Environmental Scan on the Operational Use of Remotely Piloted Aircraft Systems (RPAS) for Geomatics Applications in Canada

Analyse du contexte de l'utilisation des systèmes d'aéronefs télépilotés (drones) en géomatique au Canada

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EXECUTIVE SUMMARY

Among a wide range of Canadian industries there is a need for increased situational awareness and site-specific information that is available in a timely fashion and interpretable by local decision makers. Remotely-piloted Aircraft Systems (RPAS) play an increasingly important role to meet these information needs especially in cases where the cost, level of detail, and operational inflexibility of conventional sensor platforms (e.g., ground, manned aircraft, satellite) are limiting factors. Capable of controlled level flight even though no pilot is onboard, RPAS increase situational awareness while reducing human workloads, and accomplish many monitoring tasks at a lower cost and personnel risk, higher level of detail, and a shorter turn-around time.

To close the knowledge gaps between organizations that have already begun to use RPAS with those that are intending to do so, the goal of this report was to reduce the chance for duplication of work between organizations in their developments of RPAS-specific geomatics programs and services. The scientific literature, operational experience, and policy recommendations were synthesized to provide an overview of the technological and regulatory aspects of RPAS operations, as well as best practices and risk management strategies.

RPAS are a mature technology to derive geo-information products in Canada, and a large variety of operational platforms and sensors can serve a wide range of mapping and situational awareness applications. Autopilot technology and software for flight planning, flight guidance, and data processing is commercially available and production capable, and is highly automated. RPAS can therefore serve markets whose workforce may have little aviation or photogrammetric experience. The majority of operational RPAS applications are conducted with small RPAS and with consumer-grade cameras, over project areas not larger than 10 km^2. The majority of operational RPAS applications are comprised of oblique still photography, video footage, and photogrammetric applications (e.g., ortho-mosaic, Digital Terrain Model) whereby RPAS provide a competitive price-performance level, flexibility, and high-grade accuracies in case of mapping projects.

Updated regulations in 2017 are expected to greatly reduce the need for Special Flight Operation Certificates, which will reduce organizational risks and improve the ability to quickly respond to information needs. From a privacy stand-point the collection of personal information from RPAS are subject to the same privacy law requirements as any other data collection practice. Nevertheless, the geomatics industry has much to gain with a transparent approach through public notifications of RPAS missions, purpose specification, designating a point-of-contact, and appropriate data handling procedures. Furthermore, clear end-user license agreements should be in place to specify data rights and restrictions, particularly in the case of sensitive information.

The RPAS and associated data processing industry is rapidly growing and evolving both in Canada and globally. This advancing medium will continue to serve both existing and new geospatial information users. Improvements in platform and sensor technology, beyond visual-line-of-sight regulations, availability of Canadian RPAS test sites, earth observation research, data processing and management techniques, and data standards are required to further promote its use. RPAS also provide opportunities for improved geomatics outreach through STEM (Science, Technology, Engineering, Mathematics) opportunities and enabling community-based monitoring.

SOMMAIRE

Une grande variété d'industries canadiennes souhaite accroître leur connaissance des situations et obtenir en temps opportun des renseignements propres à un site et faciles à interpréter par les décideurs locaux. On utilise de plus en plus les systèmes d'aéronefs télépilotés, ou drones, pour satisfaire à ces besoins d'information, notamment lorsque l'on est limité par des considérations de coût, de degré de détail et de la rigidité de l'emploi des plates-formes de capteurs classiques (p. ex., au sol, en vol avec équipage, depuis un satellite). Par leur capacité de vol en palier sans pilote, les drones améliorent la connaissance des situations tout en réduisant la charge de travail humaine, et en réalisant plusieurs tâches de surveillance à moindre coût, avec un risque réduit pour le personnel, un degré plus élevé de détail et dans des délais plus courts. Nous avons produit ce rapport afin de combler les lacunes de connaissances entre les organisations qui utilisent déjà les drones et celles qui envisagent de le faire, et ainsi réduire les risques de répétition du travail d'une à l'autre lorsqu'elles créent des programmes et des services spécifiques de géomatique utilisant des drones. Nous avons synthétisé la documentation scientifique, l'expérience d'utilisation et les recommandations en matière de politique pour donner un aperçu des éléments technologiques et réglementaires de l'utilisation de drones, et des pratiques exemplaires et des meilleures stratégies de gestion des risques. Les drones constituent une technologie mature permettant d'obtenir des produits d'information géographiques au Canada. La grande variété de plates-formes opérationnelles et de capteurs permet un vaste éventail d'applications cartographiques ou de connaissance de la situation. Les technologies et logiciels hautement automatisés d'autopilotage visant la planification des missions, le guidage en vol et le traitement de données ont été commercialisés et sont prêts pour l'exploitation. Les drones peuvent donc servir les marchés où les travailleurs ont peu ou pas d'expérience en aviation ou en photogrammétrie. Dans la majorité des projets, on utilise de petits drones munis de caméras grand public au-dessus de territoires plus petits que 10 km^2. Les drones sont surtout utilisés pour la photographie oblique, les séquences vidéo et la photogrammétrie (par ex., construction de modèles topographiques numériques à partir d'ortho-images superposées), des activités pour lesquelles les drones se caractérisent par leurs coûts concurrentiels, leur flexibilité et leur grande précision dans le cadre de projets cartographiques. Nous prévoyons qu'en 2017 une nouvelle réglementation réduira grandement l'obligation de détenir un certificat d'opérations aériennes spécialisées, ce qui diminuera les risques organisationnels et accroîtra la capacité de réagir rapidement si l'on a besoin de renseignements. Du point de vue de la protection de la vie privée, la collecte par un drone de renseignements personnels fait l'objet des mêmes obligations en matière de respect de la vie privée que de toute autre méthode de collecte. Cela dit, l'industrie de la géomatique aurait beaucoup à gagner en adoptant une approche transparente par la diffusion d'avis publics des missions de drones, de précisions de leur objectif, d'indication d'un point de contact et des procédures adéquates de traitement des données. De plus, des accords de licence d'utilisation devraient être conclus afin de préciser les droits et les restrictions en matière de données, en particulier dans le cas des renseignements de nature délicate. L'industrie du drone et du traitement des données associées est en croissance rapide au Canada et à l'échelle mondiale. Ce médium en progression continuera à servir les utilisateurs actuels et futurs des renseignements géospatiaux. L'amélioration de la technologie des plates-formes et des capteurs, de la réglementation relative aux situations « hors visibilité directe », de la disponibilité de site d'essais de drones au Canada, de la recherche sur l'observation de la Terre, des techniques de traitement et de gestion des données et des normes relatives aux données sont nécessaires pour encourager l'utilisation des drones. Les drones offrent aussi des occasions pour augmenter le rayonnement de la géomatique, par des possibilités en sciences, technologie, génie et mathématiques et la surveillance communautaire.

ACRONYMS AND ABBREVIATIONS

AAT	Automatic Aerial Triangulation
AGL	Above Ground Level
APS-C	Advanced Photo System Type-C (Camera image sensor format)
ASPRS	American Society for Photogrammetry and Remote Sensing
BVLOS	Beyond Visual-Line-Of-Sight
CAR	Canadian Aviation Regulations
DSLR	Digital single-reflex (Camera design standard)
DSM	Digital Surface Model
DTM	Digital Terrain Model
EO	Electro-optical
GCP	Ground Control Point
GNSS	Global Navigation Satellite System (e.g., GPS, GLONASS)
ICT	Information and Communications Technology
IMU	Inertial Measurement Unit
LAS	LASer File Format Standard for LiDAR data sanctioned by ASPRS
LAZ	Open-source format for lossless compression of LAS files
LiDAR	Light Detection And Ranging
MFT	Micro-four-thirds (camera design and sensor standard)
MISB	Motion Imagery Standards Board (video metadata standard)
NDVI	Normalized Difference Vegetation Index
MTOW	Maximum take-off weight
NPA	Notice of Proposed Amendment (Transport Canada)
OGC	Open Geospatial Consortium
OHS	Occupational Health and Safety
PIA	Privacy Impact Assessment
PIPEDA	Personal Information Protection Electronic Documents Act
PPK	Post-Processed Kinematic
RMSE	Root Mean Square Error
ROC-A	Restricted Operator Certificate–Aeronautical (Industry Canada)
RPAS	Remotely-piloted Aircraft System (Transport Canada definition)
RTK	Real Time Kinematic
SAR	Synthetic Aperture RADAR (Radio Detection And Ranging)
SfM	Structure-from-Motion
SFOC	Special Flight Operation Certificate (Transport Canada)
SIFT	Scale-Invariant Feature Transform
SOP	Standard Operating Procedures
STEM	Science, Technology, Engineering, and Mathematics
UAS	Unmanned Aircraft System (Transport Canada definition)
UAV	Unmanned air vehicle (Transport Canada definition)
VLOS	Visual line-of-sight
VTOL	Vertical Take-Off and Landing

TABLE OF CONTENTS

1. INTRODUCTION

Unmanned aerial vehicles, Unmanned Aircraft Systems, aerial robots, or drones, are aircraft with no human pilot onboard yet are capable of controlled level flight, whereby the unit is either controlled by onboard computers and GNSS technology, or operated by remote control with a pilot on the ground. By increasing situational awareness while reducing human workloads, this technology can accomplish many monitoring tasks at a lower cost, at a higher level of detail, reduced sampling bias, greater flexibility, and increased safety (Brady 2013; Whitehead & Hugenholtz 2014; Riopel et al. 2014).

As a result the unmanned aircraft sector is rapidly growing and evolving both in Canada and across the world (Teal Group 2014; Baillie et al. 2014; Thompson & Saulnier 2015). Entrepreneurs and agencies are leveraging robotic, computer vision, and geomatics technologies to serve the needs of large-scale (e.g., 1:200) low-altitude imaging and geospatial information users (Colomina & Molina 2014; Whitehead et al. 2014). The fusion of these new technologies can be seen as a "disruptive" medium in geomatics (Percivall et al. 2015) as their application will replace to some extent the market activity of other remote sensing platforms (manned aircraft, satellites) and will by itself stimulate new markets to take advantage of their unique capabilities. As the prevalence of unmanned systems will continue to grow at a fast pace along with the regulatory environment which governs their use, there is a need for a better understanding of how these systems can be implemented operationally for various monitoring applications.

1.1. Purpose of Report

In an environment where industry, government, agencies, and regulators are faced with reduced financial resources but increasing pressures for improved monitoring, unmanned systems are being viewed as one of the potential solutions. To close the knowledge gaps between organizations that have already begun to use RPAS with those that are intending to do so, the goal of this report was to reduce the chance for duplication of work between organizations in their developments of RPAS-specific geomatics programs and services. The scientific literature, operational experience, and policy recommendations were synthesized to provide an overview of the technological and regulatory aspects of RPAS operations, as well as best practices and risk management strategies.

1.2. Outline of Report

Following a situational analysis across multiple industries currently served by the geomatics sector (Section 2), a review of applications is conducted (Section 3). Overviews of commercially available and ready-to-fly platforms and sensor payloads are provided in Section 4, after which the current and expected future regulatory environments are discussed (Section 5). Best practices for unmanned system operations in geomatics are formulated in Section 6, following risk management strategies at the operational level (Section 7). Section 8 identifies future opportunities for governments, private industry, and academia, and Section 9 summarizes the findings, identifies knowledge gaps, and provides recommendations.

1.3. Terminology

As is often the case for new technologies, a consensus on the terminology surrounding unmanned aerial technology has not yet been reached in the industry and is only slowly developing across national aviation regulatory bodies. As a result multiple unregulated terms such as *Unmanned Aerial Vehicle*, *Unmanned Aircraft Vehicle*, *Unmanned Aircraft System*, *aerial robot* or simply *drone* are frequently used in the scientific literature, policy recommendations, and media. At the time of writing the Canadian Aviation Regulations (CAR) of Transport Canada define an *unmanned air vehicle* (UAV) as a

> "*power-driven aircraft, other than a model aircraft, that is designed to fly without a human operator on board"* (CAR 101.01(1).

The difference between UAVs and model aircraft is made with respect to the total weight of the aircraft and its intended use. To be considered as a model aircraft, the aircraft must not exceed 35 kg (77.2 lbs.) and be used for recreational purposes. This excludes any commercial, governmental, academic, search-and-rescue, or volunteering purpose where monetary gain or other form of hire and reward is realized. Hire and reward is defined as

"*any payment, consideration, gratuity or benefit, directly or indirectly charged, demanded, received or collected by any person for the use of an aircraft*" (CAR 602.45).

In practical terms this means that non-recreational use includes farmers inspecting their own fields, building management companies completing inspections on their own buildings, or real-estate agents photographing their listings.

With an aim for harmonization and standardization, the International Civil Aviation Organization has introduced the concept of *Remotely-Piloted Aircraft Systems* (RPAS), a particular class of *Unmanned Aircraft Systems* (UAS). In their Notice of Proposed Amendment regarding unmanned aviation regulations, Transport Canada (2015b) sought input regarding the inclusion of these terms in their regulations (Table 1). The changes are motivated by:

- the realization that unmanned "vehicles" are in fact "aircraft",
- the realization that the physical aircraft is only one component of a system,
- the removal of the intent of the operation (recreational vs. commercial),
- the distinction between aircraft that require some sort of pilot interaction (remote control, autopilot mission planning) as opposed to fully autonomous vehicles where the mission and decisions are made by the system without any pilot involvement.

Table 1: Expected Transport Canada terms regarding unmanned aviation technology.

UAS			
RPAS			**Autonomous UAS**
Low threshold RPAS	**Small RPAS (< 25 kg)**	**Large RPAS (> 25 kg)**	**TBD**

In this environmental scan the term RPAS is used in order to familiarize readers with the proposed terminology and for consistency with the update to the regulations in the near future.

2. SITUATIONAL ANALYSIS: GEOSPATIAL INFORMATION DRIVERS

To obtain a better understanding of the potential use of RPAS in geomatics, it is important to recognize the drivers behind the information needs of the sectors that the geomatics industry serves. The following section provides a brief overview of some of the general developments in infrastructure and environmental monitoring, emergency response, and agriculture.

2.1. Infrastructure Monitoring

Government bodies and corporations are responsible for evaluating and documenting the condition of their infrastructure and updating this information regularly. Despite recent investments, over 30% of municipal infrastructure ranked “fair” or “very poor”, and would require an investment of approximately $172 billion nationally to replace these assets (Federation of Canadian Municipalities 2012). Recent increases in investments have placed considerable pressures on the capacity of municipalities to make strategic decisions. Many organizations have indicated a lack of financial resources, staff, and time to assess the state of their infrastructure accurately and in real-time (Federation of Canadian Municipalities 2012). Simultaneously, provincial asset management aims to explore innovative ways to minimize the long-term cost of maintaining infrastructure (Government of Alberta 2015; Government of Ontario 2015). Hence increases in the frequency and quality of information enable organizations to prioritize wisely (e.g., Government of Quebec 2015).

There is also a need for climate change adaptation and mitigation capacity to ensure municipal and natural resource industry infrastructure is resilient (Lemmen et al. 2014; Federation of Canadian Municipalities 2015). These risks relate to altering site hydrology and erosion rates, decreasing site stability, and changing natural disturbance regimes (Price et al. 2013). Gravel highways underlain by permafrost are susceptible to increasing ground temperatures and ecological feedbacks as a result of maintenance (Gill et al. 2014; Batenipour et al. 2014; Idrees et al. 2015). Climate change also affects the season duration and ice capacity of ice-roads (Borkovic et al. 2015). Climate change therefore requires infrastructure vulnerability assessments to determine failure consequences along with increased monitoring to ensure site stability (Environment Canada 2009; Pearce et al. 2011; Canadian Polar Commission 2014).

2.2. Environmental Monitoring

The social acceptability of natural resource projects has stimulated the ever-increasing need for baseline environmental data and ongoing monitoring. Monitoring programs are both budget- and human resource intensive due to the remoteness and inaccessibility of the landscapes where some of these projects are proposed or occur. Challenges regarding safety, cost, geographical coverage, and logistics impede fieldwork on the ground or aerial surveys from manned aircraft. These combined factors hinder the collection of comprehensive datasets and challenges the quantification of cumulative effects of climate change and resource development. Further monitoring data is needed to better understand baseline conditions, assess change, and guide adaptive strategies, especially in Canada’s North (Canadian Polar Commission 2014). Of particular interest are multi-scale monitoring systems that integrate ground-based data with regional observations to estimate changes over larger areas (Price et al. 2013; Canadian Polar Commission 2014).

2.3. Emergency Management and Disaster Response

Canada is exposed to a wide range of natural and human-induced hazards (e.g., floods, landslides, hazardous waste accidents) as a result of its wide diversity of landforms, weather types, and industries. These hazards have the potential to become costly disasters when they encounter human vulnerabilities. During the response phase of a disaster public safety officials need to have an accurate understanding of the situation on the ground (i.e., situational awareness), including the types and extent of impacts and the availability of access to affected areas. The impact of this information is greatest during the initial response period, whereby delays in information retrieval reduce its relevance and accuracy.

In the last ten years a paradigm shift from disaster recovery towards risk reduction and mitigation has increased the importance of effective planning and preparedness (Henstra & McBean 2005; Joakim & Doberstein 2013), especially given the rising costs associated with natural disasters (Global News 2013). Most emergencies in Canada are local in nature and are managed by the municipalities or at the provincial or territorial level (Public Safety Canada 2011). Local governments and emergency services are committed to providing the best possible service to minimize the loss of life, injury, and damage, but issues related to a lack of access to information, resources, organizational capacity, and cross-agency coordination have been raised (Federation of Canadian Municipalities 2006; Joakim & Doberstein 2013). In recognition of the risks and costs of flooding, the recently announced federal National Disaster Mitigation Program funds risk assessments, flood-mapping, mitigation planning, and mitigation projects (Public Safety Canada 2015). Programs such as these highlight the need for up-to-date information and situational awareness of physical structures at risk (e.g., bridges, roads) and the structures designed to mitigate the impact of hazards (e.g., floodways, dykes, diversions, upstream storage).

2.4. Agriculture

The world population reached 7.3 billion as of mid-2015 and is projected to increase to more than 8.5 billion in 2030, and 9.7 billion in 2050 (United Nations 2015). Food production must grow substantially for meeting the world's future food security while reducing agriculture's environmental footprint (Food and Agriculture Organization 2014). Foley et al. (2011) demonstrated that food production can be doubled and environmental impacts lessened by halting agricultural expansion, closing yield gaps on underperforming lands, increasing cropping efficiency, shifting diets, and reducing waste. To achieve some of these goals agricultural practices should consider the diversity in site-specific conditions (Food and Agriculture Organization 2014).

Precision agriculture is a strategy to use multiple streams of information to adapt to site-specific conditions (Oliver et al. 2013; Cambouris et al. 2014). This strategy involves more precise seeding and input applications (fertilizer, irrigation, pesticide) rather than uniform applications. This requires knowledge of the spatial variation of soil properties, topography, crop development, pests, and weeds, from which variable rate applications or broader management zones can be established (Cambouris et al. 2014). Precision agriculture falls within a general trend of increased access to ICT technologies that exchange knowledge (e.g., crop prices, weather conditions) to do the right things in the right place at the right time (KPMG 2013; Food and Agriculture Organization 2014).

3. RPAS UTILIZATION

3.1. Why Remotely Piloted Aircraft Systems?

The analysis of geospatial information drivers indicated an increasing need for situational awareness and site-specific information that is accessible and interpretable to local decision makers. Technological advancements in the miniaturization of sensors (Global Navigation Satellite System; GNSS, Inertial Measurement Unit; IMU, imaging) and image processing (3D surface reconstruction) have created a unique opportunity for implementing new RPAS-based solutions that can be used by geomatics professionals and non-specialists. These developments are part of fundamental shifts in the geomatics industry where market demand has moved from the production of base information to value-added products and where non-specialists have become data producers as well (Natural Resources Canada 2015). The end-users' desire to access highly detailed information at the right time has increased the demand for real-time information and modeling, particularly in cases where decision makers request a comprehensive operating picture on which to base immediate decisions (United Nations 2013).

Within this context, RPAS are suited for applications where the cost, level of detail, and/or operational inflexibility of conventional sensor or surveying platforms (e.g., satellite, manned aircraft) limits near-real time delivery of information. Unmanned systems have proven they can enhance situational awareness, reduce human workload, shorten information turn-around time, minimize overall risk to personnel, and reduce costs (Whitehead & Hugenholtz 2014; Siebert & Teizer 2014). Unmanned systems provide persistence, versatility, and reduced risk to human life, especially for missions that are characterized as dull, dirty, or dangerous:

- **Dull** missions involve long-duration undertakings with mundane tasks that are not optimally suited for personnel. Good examples are intelligence missions that involve prolonged focused observation (e.g., strip-transect vegetation/wildlife surveys).
- **Dirty** missions have the potential to expose personnel to sites with limited ground accessibility (e.g., forests, wetlands, rivers, challenging topography). Unmanned systems can perform these dirty missions with less risk exposure to the operators.
- **Dangerous** missions involve high risk and expose personnel to highly dynamic or hazardous site conditions (e.g., mine sites, wildfire, collapsed infrastructure).

In addition, in-house RPAS capabilities or dedicated supply service agreements with RPAS vendors can offer a wide range of benefits to meet organizational mandates (Table 2).

Table 2: RPAS benefits with respect to organizational mandates.

Benefit	**Description**
Availability	Increased availability of time- and GNSS-stamped permanent records of features
Flexibility	Not dependent on a third-party service that requires scheduling, planning, and procurement (i.e., near real-time delivery and decision making).
Representativeness	Captures greater detail than ground surveys and can be of similar accuracy as LiDAR
Authoritativeness	Provide data from a trusted, dependable, independent source
Ownership	Provide common datasets that can be shared for cross-agency monitoring of baseline conditions, permitting, and community outreach

Awareness of these benefits have resulted in Canadian investments in RPAS technology and training to foster innovation and new economic activities in this rapidly growing industry (Table 3). Further demonstrating this awareness can be highlighted through the exponential growth in the number of scientific publications (Whitehead & Hugenholtz 2014; DeBell et al. 2015). Dedicated Canadian-based scientific journals (e.g., Journal of Unmanned Vehicle Systems - NRC Research Press), and international RPAS conferences held in Canada (e.g., UAV-g 2015 International Conference on Unmanned Vehicles in Geomatics, York University, 2015; UnmannedCanada Conferences 2003-2016) are additional indicators of sector awareness and growth.

Table 3: Reported investments in RPAS technology and training.

Funding agency	**Receiving agency**	**Amount**	**Purpose**
NSERC (2008-2020) [1]	York University	$0.27m	To develop low lost RPAS for mapping
Gov. of Canada (2013)	Aéroport d'Alma	$2.5m	To develop the UAS Center of Excellence
Gov. of Canada (2014)	ING Robotics	$0.35m	To develop and commercialize mapping-grade RPAS
Natural Research Council [2]	Multiple organizations	>$10m	Technology developments and mission-oriented demonstrations
Gov. of Canada (2015b)	Univ. of New Brunswick	$0.1m	To develop new UAS equipment to monitor Canada's forests
NSERC (2015)	Univ. of Calgary	$0.4m	To develop and demonstrate RPAS mapping accuracies
NSERC (2015)	Univ. of Toronto	$1.6m	To train 150 students in the use of UAS for agriculture and environmental monitoring
Gov. of Canada (2015a)	Univ. of Victoria	$0.5m	To advance UAS research and integration
Gov. of Canada (2015c)	Saskatchewan Polytechnic	$0.35m	To train natural resource technology students

[1] C. Armenakis 2016, pers. comm., June 5.

[2] In Baillie et al. (2014).

3.2. Overview of Applications

3.2.1. Scope

Among jurisdictions (Transport Canada, U.S. Federal Aviation Authority) and scientific publications different parameters (e.g., weight, range, and altitude), thresholds, and nomenclature are used to classify UAS systems. This challenges the understanding of expected capabilities and performance. An amalgamation of classifications provided clarifications of UAS characteristics (Table 4) and narrowed the scope to portable micro- and small- RPAS capabilities that fall under the proposed "low threshold and "small" RPAS categories of Transport Canada (Table 1).

Table 4: Classification of RPAS platforms (after United States Department of Transportation (2013)).

Type	Example Platform	Size (ft.)	Weight (lb.)	Endurance (hr)	Range (km)	Cost (USD)*
Portable						
Nano	Hummingbird	< 1	< 1	< 0.5	< 0.5	-
Micro	DJI Phantom	< 3	1 - 5	< 0.5	0.5 – 5	500 - 10k
Small	Precisionhawk Lancaster	< 10	5 - 55	0.5 - 4	5 – 25	10k – 50k
Tactical						
Ultralight	Boeing RQ-21 Blackjack	< 30	55 – 255	4 – 6	25 – 50	50k – 100k
Lightsport	AAI RQ-7 Shadow	< 45	255 – 1,3k	6 – 12	50 – 100	100k - 800k
Small	GA Predator	< 60	1,3k – 12,5k	24 – 36	100 - 200	800k – 15m
Strategic						
Medium	Global Hawk	> 60	12,5k – 41k	> 36	Global	15m - 130m

* Platforms are typically part of a system. Total system cost is higher for tactical and strategic systems.

3.2.2. Scientific Advancements

The emphasis of the scientific literature and third-party operational services is generally limited to small RPAS flying at low altitudes (< 120 m) within visual line-of-sight (1-10 km^2 total coverage per day), while carrying small compact or medium-format cameras (Colomina & Molina 2014; Whitehead & Hugenholtz 2014). This emphasis is a result of the cost-effectiveness of small RPAS, the inherent complexity of operating larger tactical RPAS, and the existence of straight-forward airspace regulations authorizing research use of smaller RPAS. Scientific investigations have spanned a wide range of industries and information gaps (Table 5), with exponential growth in the number of publications (Whitehead & Hugenholtz 2014; DeBell et al. 2015).

Table 5: Peer-reviewed RPAS applications.

Sector	Information Gap	Reference
Surveying, Earthworks, Infrastructure Monitoring	Fracture orientation of open-pit mine	(Mcleod et al. 2013)
	Power-line monitoring	(Kuhnert & Kuhnert 2013)
	Earthworks volumetrics	(Whitehead et al. 2014)
	Earthworks volumetrics	(Cryderman et al. 2014)
	Earthworks volumetrics, as-built survey	(Siebert & Teizer 2014)
	Photo-voltaic plant inspections	(Quater et al. 2014)
	Sandpit surveys	(Wiseman & van der Sluijs 2015)
	Surface road conditions underlain by permafrost	(Fraser et al. 2015)
	Inspection, maintenance of oil/gas infrastructure	(Shukla & Karki 2016)
Environmental monitoring	Differentiation of rangeland vegetation	(Laliberte et al. 2011)
	Geomorphology	(Hugenholtz et al. 2013)
	Wetland vegetation	(Chabot & Bird 2013)
	3D measurements of coastal environments	(Mancini et al. 2013)
	Glacier monitoring (thinning, motion)	(Whitehead et al. 2013)
	Vegetation, disaster response, wildlife, hydrology	(Shahbazi et al. 2014)
	Brown trout river habitat, salmon spawning events	(Whitehead et al. 2014)
	Distribution of water sources, sinks, and flows	(DeBell et al. 2015)
	Riparian health assessment	(NSWA 2015)*
	Wildlife aerial surveys	(Chrétien et al. 2015)
	Wildlife aerial surveys	(Linchant et al. 2015)
	Permafrost thaw slump and tundra vegetation change	(Fraser et al. 2015)
	Well-site reclamation	(Hird & McDermid 2015)
	Glaciology	(Bhardwaj et al. 2016)
Emergency Response	Disaster management (review)	(Griffin 2014)
	Environmental spill response	(Partington 2014)
	Search-and-rescue	(RCMP 2014)
Agriculture	Cereal lodging, insect infestations, tile drainage	(Zhang et al. 2014)
	Canola field trials, tile drainage	(Kostuik 2014)
	Late blight detection, cattle enumeration	(Whitehead et al. 2014)
	Crop health/vigour (vineyard/tomato)	(Candiago et al. 2015)
	Vegetation water stress	(Gago et al. 2015)
	Soil moisture	(Hassan-Esfahani et al. 2015)
	Nitrogen-fixing cover crop coverage (red clover)	(Abuleil et al. 2015)
Forest Management	Canopy gaps	(Getzin et al. 2014)
	Tree height	(Zarco-Tejada et al. 2014)
	Forest fire impacts	(Wing et al. 2014)
	Forest inventory: Lorey's mean height, dominant height, stem density, basal area, stem volume	(Puliti et al. 2015)

* NSWA: North Saskatchewan Watershed Alliance.

3.2.3. Operational Applications

Despite an exponential growth of RPAS in the scientific community, the emerging literature to-date has focused on sensor experiments and potential applications rather than mature, routine and operational uses (Whitehead et al. 2014; Shahbazi et al. 2014). Although the studies represent applications suitable to current generation of small UASs, most require careful data processing and experimental designs to model the parameters of interest. Further research is required before standardized information products can be provided as a key-turn solution (Zhang & Kovacs 2012; Candiago et al. 2015). In contrast, aerial photographs and video acquired through RPAS can provide a wealth of qualitative information to end-users without computational complexities. For example, forestry specialists can use RPAS-derived ortho-mosaics for updated information on pre- and post-harvest conditions and compliance monitoring of harvest boundaries (Launchbury 2014), while time- and GNSS-stamped photographs and video can provide up-to-date site documentation and situational awareness during time-sensitive events (Griffin 2014). This means that RPAS can provide a wide range of operational and straight-forward geomatics applications for small to regional scale work (< 10 km^2) in areas that are currently difficult or expensive to access (Table 6). These are applications that can be readily implemented as operational procedures and which consist of the lowest possible barriers for deployment.

Table 6: Overview of operational RPAS applications.

Sector	Application
Surveying, Earthworks, Infrastructure Monitoring	Volumetric analysis of rock, sand, and gravel resources Structure inspections 2D/3D maps for as-built surveys and engineering plans Oblique aerial photography for resource documentation/promotion Inspections (video/still) of live equipment (flares, exhausts) Health & safety inspections (e.g., weather damage, damaged objects) Support for Annual Inspection Plans (structural/pressure) to target repairs
Environmental monitoring	Oblique aerial photography for site documentation Aerial photography of crime scenes (wildlife infractions) Riparian and wildlife health observations (video) Manual wildlife counting Ortho-mosaics for mine remediation status Ortho-mosaics for well-site regeneration status 3D maps for identification of landslides 3D maps for permafrost thaw mapping Ortho-mosaics for mine remediation status Ortho-mosaics for well-site regeneration status
Emergency response	Aerial photography for environmental spill response documentation Missing person detection through real-time thermal video downlink Incident situational awareness (updated ortho-mosaics, real-time video)
Agriculture	Ortho-mosaics (visible, vegetation index) for manual crop scouting Oblique aerial photography for farm documentation Ortho-mosaics for manual crop lodging, infestations, drainage inspections
Forest management	Oblique aerial photography for site documentation Oblique aerial photography/video for prescribed burns Ortho-mosaics for cutblock planning / compliance audits Ortho-mosaics photos for site selection for fieldwork 3D maps for regeneration surveys 3D volume assessment of harvested logs/woodchips

3.3. Photogrammetric Mapping Capabilities

3.3.1. Horizontal and Vertical Accuracies

Numerous studies have demonstrated the ability of RPAS to derive ortho-mosaics and Digital Terrain Models (DTMs), in which accuracy was measured against conventional techniques such as differential GNSS measurements or Light Detection and Ranging (LiDAR) (Hugenholtz et al. 2013; Mancini et al. 2013; Cryderman et al. 2014). It is difficult to extrapolate these results as accuracy is a function of the surface being mapped, the measurement technique used to collect reference data, the image scale, and the image processing software (Aguilar et al. 2007; Höhle & Höhle 2009; Colomina & Molina 2014). Nevertheless, some general expectations and levels of agreement can be formulated. To do so requires differentiation between the mean error (i.e., the systematic under- or over-estimation of elevation values compared to more accurate data) and the Root Mean Square Error (RMSE; the absolute fit of the elevation model to more accurate data) (Höhle & Höhle 2009).

For some applications the collection of ground control points (GCPs) to improve RPAS model accuracy is cumbersome and not needed to meet the requirements of the deliverables (e.g., time, cost, accuracy). In these cases the absolute accuracy of the mapping deliverables are governed by the GNSS module of the autopilot, and generally range between 2 m – 10 m RMSE horizontally and vertically (Skarlatos et al. 2013; Küng et al. 2011; DeBell et al. 2015). The relative horizontal and vertical RMSE accuracy of the ortho-mosaic or DTMs, defined as the closeness of relative spatial positions, is generally between 1 to 3 times the spatial resolution of the imagery (e.g., 3 cm – 9 cm RMSE for 3 cm spatial resolution imagery) (Mesas-Carrascosa et al. 2015; Pix4D 2015a).

Ground control points are required when the specifications of the mapping product dictate a higher level of accuracy. Accuracy generally improves with one order of magnitude when GCPs are used (Clapuyt et al. 2015), whereby mean vertical accuracies range between 0.01 m - 0.14 m (Hugenholtz et al. 2013; Mancini et al. 2013; Cryderman et al. 2014). In terms of fitness for use, RPAS have derived accuracies between 0.03 m - 0.18 m horizontal RMSE and 0.03 m - 0.22 m vertical RMSE (Rosnell & Honkavaara 2012; Hugenholtz et al. 2013; Mancini et al. 2013; Whitehead et al. 2014; Whitehead & Hugenholtz 2015). These generally translate to an accuracy of 1 to 2 times the spatial resolution in horizontal coordinates and between 1.5 and 3 times the spatial resolution in vertical coordinates. Hence the absolute accuracy is strongly dependent on the spatial resolution of the raw images. The reported accuracies indicate that RPAS can derive vertical accuracies that are on par with LiDAR under certain conditions (e.g., Hugenholtz et al. 2013).

Direct geo-referencing can be used when the collection of GCPs is not possible, impractical, or too costly. Realized through improvements in the accuracy and miniaturization of small high-grade differential GNSS units and IMU, direct georeferencing is a technique to derive highly accurate positioning and orientation of the RPAS imagery without the need for GCPs. Ortho-mosaics with mean horizontal accuracies ranging between 0.12 m - 0.25 m have been reported using a single-frequency (L1) differential GNSS (Turner et al. 2014). Further improvements can be achieved through the use of dual-frequency (L1/L2) differential Post-Processed Kinematic (PPK) or Real Time Kinematic (RTK) GNSS sensors, with horizontal RMSE ranging between 0.03 m and 0.09 m and vertical RMSE ranging between 0.04 m and 0.11 m (Roze et al. 2014; Mian et al. 2015).

3.3.2. Stockpile Volume Estimates

As accuracies of RPAS-derived DTMs can approximate LiDAR-grade elevation models under certain conditions, it is not uncommon for aggregate volumetric comparisons to differ between 0.7 – 3.9 % relative to differential GNSS surveys (Cryderman et al. 2014; Whitehead et al. 2014). Volumetric comparisons between flights appear to be robust, as Cryderman et al. (2014) found a 0.2 % difference between flights of the same pile and Clapuyt et al. (2015) found a mean difference of 0.06 m between datasets acquired by consecutive missions.

The studies reporting on horizontal, vertical, and volume accuracies demonstrate that RPAS photogrammetry can be sufficient for 1:200 scale mapping and 0.145 m contour intervals, and can be equivalent in accuracy to PPK or RTK GNSS surveys when measuring stockpile volume and volume changes (Barry & Coakley 2013; Cryderman et al. 2014). Within a broader context, RPAS photogrammetric surveys can meet the accuracy requirements for Class 1 of the 1990 ASPRS standards (1:500 scale, 0.5 m contour interval), and the 10 cm RMSE level requirements for horizontal and vertical mapping under the newly developed 2015 ASPRS standards (Whitehead & Hugenholtz 2015; ASPRS 2015a). In addition to providing a greater level of detail relative to point-specific GNSS surveys (Cryderman et al. 2014), RPAS surveys provide greater spatial coverage in comparison to GNSS surveys (Figure 1).

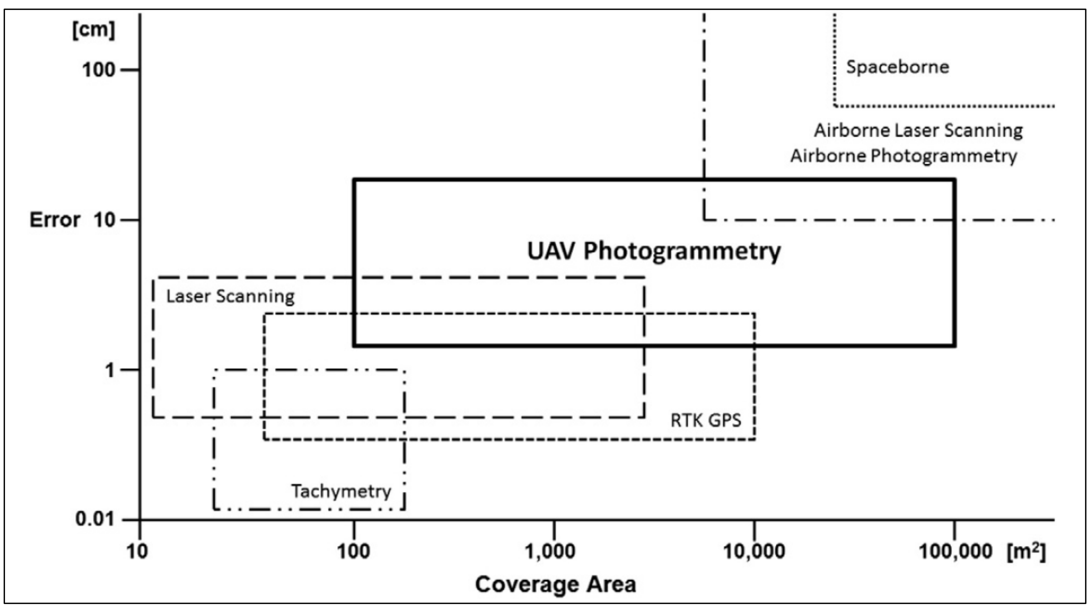

Figure 1: Coverage areas and associated survey errors for a variety of methods (Siebert & Teizer 2014).

4. RPAS TECHNOLOGY OVERVIEW

A RPAS is a set of complementary technologies designed to fulfill a specific task (Colomina & Molina 2014). Due to the breadth of different GNSS, IMU, autopilot, and imaging sensor components a wealth of options exists for potential RPAS users in Canada. A scan of RPAS platforms and sensor payloads was conducted in March 2016 to highlight commercially available systems that are "ready-to-fly" and fully integrated with respect to sensor payload and ground control station (i.e., operational systems). The scope of this review was limited to RPAS and sensors that were available through Canadian and United States manufacturers, vendors, or official resellers, and were up to 25 kg in total weight (i.e., small RPAS). Instead of selecting a platform on which to base the sensor and application, it is generally advised to 1) determine the application(s) for the RPAS, 2) identify the required sensor, 3) evaluate the operating environment and mission requirements, and 4) select the appropriate RPAS platform. This sequence ensures that the acquired data can fill the information gaps of the subject matter experts. In practice a balance must be struck between platform and sensor characteristics (weight, power, resolution, accuracy, precision), and costs.

4.1. Payloads Available Within the <25 kg RPAS Category

4.1.1. General Considerations

There is currently a wide range of sensors that can be installed on a RPAS. Sensors are typically grouped by the way they operate (passive, active), sensitivity to the electromagnetic spectrum, and the number of spectral bands or modes. Passive sensors require a naturally occurring source of energy (i.e., sunlight) to observe the target, whereas active sensors provide their own energy source that is directed towards the target under investigation. RPAS sensors feature quality grades that range from low-cost amateur markets to professional and even military markets. In addition, there are those sensors that were designed without RPAS in mind but that are readily integrated, and those that have been specifically designed to meet the challenges of RPAS operations. The following sections provide descriptions and rationales for sensors available for RPAS missions.

4.1.2. Passive Sensors

4.1.2.1. Visible sensors

Visible electro-optical (EO) sensors capture images or video footage within the visible wavelength range of the electromagnetic spectrum (0.4 – 0.7 μm), which is the range that human eyes can naturally see (Figure 2). Visible EO sensors detect the red, green, and blue portions of light which are mixed together to produce images that humans can easily interpret. Commercial off-the-shelf options provide straight-forward access to visible imagery and there are numerous options that can meet any budget. Their size and price ranges from consumer-grade compact point-and-shoot cameras and professional mirrorless interchangeable lens cameras (Micro-Four-Thirds; MFT, Advanced Photo System Type-C; APS-C, Digital Single-Lens-Reflex; DSLR) to industrial and military grade custom-designs. They feature image sensors whose resolution usually varies between a few to tens of megapixels. This results in the acquisition of imagery at a spatial resolution of a few millimeters to several centimeters depending on the focal length of the lens and mission altitude.

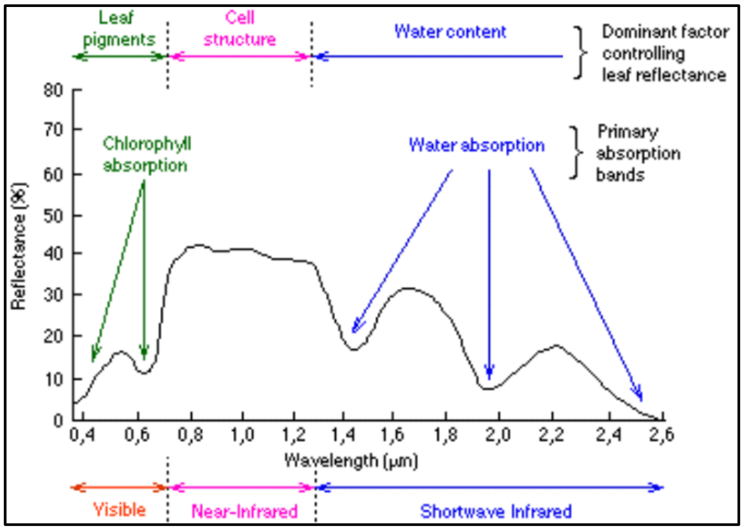

Figure 2: Reflectance of vegetation across the electromagnetic spectrum (NASA, 2002).

Visible EO sensors are generally used for the production of ortho-mosaics and site-specific three-dimensional reconstructions or video across many disciplines (Table 5). The differences in costs relate to the size of the physical sensor and the quality of the lens among other variables. The quality of the camera is positively related to the accuracy of the final mapping products (Rosnell & Honkavaara 2012). For most applications a balance of accuracy and cost can be struck by selecting an APS-C camera, such as a Sony A6000, as they are smaller and lighter than a DSLR yet acquire images at a higher quality than compact digital cameras.

Table 7: Overview of Visual EO Sensors Offered in Operational RPAS Platforms.

Manufacturer	**Model**	**Type**	**Megapixels**	**Focal Length (mm)**
Aeryon	HDZoom30	Custom	20	-
Aeryon	SR-3SHD	Custom	15	-
Aeryon	SR-EO/IR	Custom		-
Canon	S110	PAS	12	24
DJI	Zenmuse X3	Custom	12	20
DJI	Zenmuse X5	Custom	16	Interchangeable lens
DJI	Zenmuse X5R	Custom	16	Interchangeable lens
DreamQii	BublCam	Custom	5	-
GoPro	Hero3+ Black	Custom	12	14, 21, 28
GoPro	Hero4 Silver	Custom	12	-
GoPro	Hero4 Black	Custom	12	-
Lockheed Martin	OnPoint	Custom	10	-
Olympus	E-P3	Mirrorless	12	Interchangeable lens
Pentax	Optio S1	PAS	14	28
Phase One Industrial	IXU 1000	Custom	100	Interchangeable lens
PrecisionHawk	Visual	Mirrorless	18	18
Ricoh	PX	PAS	16	28
Sensefly	WX	PAS	18	25
Sony	RX100 III	PAS	20	24
Sony	A5100	Mirrorless	24	Interchangeable lens
Sony	A6000	Mirrorless	24	Interchangeable lens
Sony	A7R	DSLR	36	Interchangeable lens
Sony	NEX-7	Mirrorless	24	Interchangeable lens

PAS: point-and-shoot camera. Focal length reported at 35-mm equivalent.

4.1.2.2. Multi-spectral sensors

Multi-spectral EO sensors capture images within and beyond the visible portion of the electromagnetic spectrum (0.4 – 1.25 μm). It is the near-infrared portion of the spectrum where vegetation reflects a significant amount of incoming sunlight, enabling vegetation-specific mapping applications through remote sensing (Figure 2). Reflectance from healthy vegetation is at its highest beyond 0.8 μm (i.e., the near-infrared spectral plateau), while stressed vegetation is considerably lower. Near-infrared sensors used for RPAS mapping can generally be divided into two categories, comprising wide-band modified cameras and purpose-built narrow-band cameras. The differences are related to the quality and reliability of the image output, and the cost of the sensor.

Modified cameras represent a less costly approach to capture near-infrared data by converting a commercially off-the-shelf visible camera. Most digital cameras use a Bayer pattern array, which is a mosaic of selectively transmissive filters to capture red, green, and blue light. Each pixel in the Bayer array is sensitive to only one portion of the electromagnetic radiation (i.e., red, green, or blue) whereby the other colours are interpolated from neighbouring pixels to produce a seamless visible image. Bayer-pattern filters transmit some near-infrared light, and camera manufacturers use an internal hot-mirror filter blocking this near-infrared light to obtain high quality images in the visible portion of the spectrum (Hunt et al. 2010; Whitehead & Hugenholtz 2014). In order to capture near-infrared data, this filter is removed and replaced by a filter that either converts the blue channel to be sensitive to the near-infrared wavelength or a filter that blocks red wavelengths to remain only sensitive in the blue, green, and near-infrared portions of the spectrum (Hunt et al. 2010; Nijland et al. 2014; Proctor & He 2015).

There are several important considerations that RPAS operators and data users should make when selecting modified near-infrared sensors or using the data derived through these sensors (Section 7.3). Near-infrared measurements and Normalized Difference Vegetation Index (NDVI) values derived from modified cameras cannot be reliably compared through time, and these sensors are not suitable for quantitative spectral analyses or thematic mapping applications (e.g., land-cover classification, feature detection) (Whitehead & Hugenholtz 2014). Instead, their use is qualitative and can provide general insights into vegetation patterns (e.g., vegetated versus non-vegetated) that allow for within-field comparisons at the time of capture. With their use comes the expectation that the models may not be consistent between areas or comparable through time.

Purpose-built near-infrared EO sensors can provide quantitative data albeit at a higher cost and lower pixel resolution than modified consumer cameras. These sensors capture reflected light in narrow bands and have a known spectral response that is determined by the manufacturer. They require calibration targets on the ground to adjust for changing light conditions and to convert the raw imagery to absolute reflectance values. Recent advancements allow the acquisition of onboard irradiance measurements (i.e., incident light) as part of the data acquisition (Näsi et al. 2015; Parrot 2016), however careful post-processing of irradiance data is required due the sensitivity of raw measurements towards different angular positions of an airborne platform (Homolova et al. 2009). When converted to absolute reflectance values, the measurements and derived NDVI values should be consistent through time (all else being equal) and provide comparable data. As a result, many studies have found successes with sensors produced by manufacturers such as Tetracam (Berni et al. 2009; Laliberte et al. 2011; Kelcey & Lucieer 2012; Peña et al. 2013; Zhang et al. 2014; Candiago et al. 2015). An additional indicator of these successes is the recent increases in the availability of narrow-band sensors by manufacturers such as Airinov (sensor: multispec4c) and Micasense (sensors: RedEdge, Sequoia). However, more often than not complicated post-processing sequences are required to obtain consistent data. For example, raw multispectral data requires: 1) co-registration of images, 2) a dark current correction, 3) a radiance strength modification, 4) a vignetting correction, 5) a lens distortion correction, 6) and the conversion of digital numbers to radiance and reflectance (Kelcey & Lucieer 2012). These pre-processing procedures are typically implemented through custom scripts which limit the uptake of these protocols beyond the scientific community. Hence there is a need for more standardized and user-friendly approaches (e.g., sensor metadata, software) to reach the full potential of these sensors at the operational level.

Table 8: Overview of Multispectral EO Sensors Offered in Operational RPAS Platforms.

Manufacturer	Model	Type	Bands	Megapixels	Focal Length (mm)
Canon	S110 NIR (converted)	PAS	3	12	5.2
Canon	S110 RE (converted)	PAS	3	12	5.2
MAPIR	NDVI Blue+NIR	Custom	2	12	4.35
MicaSense	RedEdge	Custom	5 + Irradiance	1.6	5.5
MicaSense	Sequoia	Custom	4 + Irradiance	1.2	-
PrecisionHawk	Multispectral	Custom	6	7.8	9.6
Sensefly	multiSPEC 4C	Custom	4	4.8	-
Skysquirrel	DroneFuse	Custom	5	-	-
Sony	A5100 (converted)	Mirrorless	3	24.3	Interchangable lens
TetraCam	ADC Lite	Custom	3	3.2	8
TetraCam	ADC Micro	Custom	3	3.2	8.43
TetraCam	ADC Snap	Custom	3	1.3	8.43
TetraCam	Micro MCA	Custom	4,6,12	3.2	9.6

4.1.2.3. Hyperspectral sensors

Remote sensing with hyperspectral sensors concerns imaging the Earth surface with narrow spectral bands over a continuous spectral range. Whereas multispectral sensors acquire images of a few discrete bands and provide general reflectance information of distinct spectral regions, hyperspectral sensors detect reflected light in tens to hundreds of narrow bands. As a result they acquire a detailed spectral characterization of each imaged object in comparison to multi-spectral sensors, enabling applications related to vegetation health (e.g., moisture stress, nutrient deficiencies) and advanced land-cover and feature detection extraction.

These sensors have not yet reached an operational status as a result of costs, the limited availability of sensors that are readily integrated through turn-key solutions, and the lack of standardized and user-friendly image pre-processing approaches. For example, the image miniaturization process to develop hyperspectral sensors for RPAS is challenged by optics and sensor calibration (Honkavaara et al. 2013; Lucieer, Malenovský et al. 2014; Näsi et al. 2015; Proctor & He 2015). Issues related to geometric corrections (rolling shutters, sensor drift, sensor stabilization, band-to-band georeferencing), radiometric corrections (bi-directional reflectance, atmosphere), and sensor size, weight and power have limited the current application of hyperspectral sensors to scientific studies. There are considerable subtle technical parameters that determine sensor performance (e.g., cross-talk, optical distortions, variability per wavelength, quantum efficiency, signal-to-noise ratio), and the lack of a common industry standard for measuring and documenting instrument performance challenges the evaluation of the operational suitability for RPAS applications (Proctor & He 2015). Hyperspectral sensors feature a reduced pixel resolution (1-2 megapixels) in comparison to wide-band sensors, which translates to a coarser spatial resolution (e.g., 15 - 40 cm) when flown at the maximum altitudes allowed by aviation regulations. Rotary-wing RPAS are the most suitable platform for hyperspectral missions, as slow flights (< 10 m/s) are required to accommodate the longer integration time typical of hyperspectral sensors and to improve the signal-to-noise (Lucieer, Malenovský et al. 2014). With these challenges in mind, RPAS operators are advised to test these sensors to ensure that they meet the radiometric and geometric requirements of the application (Whitehead & Hugenholtz 2014).

Table 9: Overview of Hyperspectral EO Sensors Offered in Operational RPAS Platforms.

Manufacturer	Model	Bands	Wavelength (μm)	Swath (Pixels)	Weight [1] (kg)
Headwall Photonics	Nano-Hyperspec VNIR	270	0.4 – 1.0	640	0.5
Headwall Photonics	Micro-Hyperspec VNIR-A	324	0.4 – 1.0	1004	0.7
Headwall Photonics	Micro-Hyperspec VNIR-E	369	0.4 – 1.0	1600	1.1
Headwall Photonics	Micro-Hyperspec VNIR-B	100	0.9 – 1.7	525	0.9
Headwall Photonics	Micro-Hyperspec VNIR-BE	199	0.6 – 1.7	525	0.9
Headwall Photonics	Micro-Hyperspec SWIR-M	166	0.9 – 2.5	384	2.0
Rikola	Hyperspectral Camera	380	0.5 – 0.9	1010	0.7
Rikola	Hyperspectral Camera	380	0.4 – 0.7	1010	0.7
Rikola	Hyperspectral Camera	380	0.45 – 0.8	1010	0.7
Rikola	Hyperspectral Camera	380	0.55 - 9.5	1010	0.7

[1] Without lens.

4.1.2.4. Thermal sensors

Thermal sensors capture heat signatures in the infrared portion of the electromagnetic spectrum (3 μm - 15 μm). Each object with a temperature above absolute zero (-273.15°C = 0 Kelvin) emits electromagnetic radiation from its surface, which is proportional to its temperature. Thermal sensors detect the amount of infrared light emitted from the Earth's surface and assign brightness values to produce false-colour images that humans can interpret. Imagery which portrays relative temperature differences in their spatial locations are usually sufficient for most RPAS applications (Zhang et al. 2015), yet absolute temperature measurements are possible pending accurate calibrations using temperature references (Berni et al. 2009; Zarco-Tejada et al. 2012). For example, thermal sensors feature automatic gain control which automatically convert the amount of infrared light to brightness values to render images with appropriate contrast, yet because of this feature distorted and highly variable thermal mosaics are produced when these individual images are mosaicked without corrections (Zhang et al. 2015). Because energy decreases with increasing wavelength, thermal sensors have a reduced pixel resolution to ensure that enough energy reaches the sensor for reliable measurements. Despite their reduced spatial resolutions, thermal sensors exploiting relative temperature differences have reached an operational status as they have been integrated into RPAS as a turn-key solution for real-time applications such as search-and-rescue, thermal heat loss inspections, and fire monitoring (Figure 1; Whitehead & Hugenholtz 2014).

Table 10: Overview of Thermal Sensors Offered in Operational RPAS Platforms.

Manufacturer	**Model**	**Wavelength (µm)**	**Resolution (pixels)**	**Focal Length (mm)**
Aeryon	SR-EO/IR	-	640 x 480	-
DJI	Zenmuse XT	7.5 – 13.5	640 x 512	7,9,13,19
DJI	Zenmuse XT	7.5 – 13.5	336 x 256	7,9,13,19
FLIR	Vue	7.5 - 13	640 x 512	9, 13, 19
FLIR	Vue	7.5 - 13	336 x 256	6.8, 9, 13
FLIR	Tau 2 (640)	7.5 - 13	640 x 512	7.5 - 100
FLIR	Tau 2 (336)	7.5 - 13	336 x 256	7.5 - 100
FLIR	Tau 2 (324)	7.5 - 13	324 x 256	7.5 - 100
FLIR	Quark (640)	7.5 - 13	640 x 512	6.3 – 25
FLIR	Quark (336)	7.5 - 13	336 x 256	6.3 – 25
Thermoteknix Systems	MIRICLE 307K	8 - 12	640 x 480	14 - 75
Thermoteknix Systems	MIRICLE 110K	8 - 12	384 x 288	14 - 75
Sensefly	thermoMap	8 - 14	640 x 512	-
UAV Solutions	Dragonview	7.5 – 13.5	640 x 512	13, 19, 25
UAV Solutions	Dragonview	7.5 – 13.5	336 x 256	13, 19, 25
Workswell	Thermal Vision	-	640 x 512	7.5, 9, 13, 19
Workswell	Thermal Vision	-	336 x 256	7.5, 9, 13, 19

Figure 1: Real-time thermal infrared video-downlink during the worlds' first successful and documented use of a RPAS in a search-and-rescue situation (Saskatoon RCMP, 2013).

4.1.3. Active sensors

4.1.3.1. Light Detection and Ranging (LiDAR)

LiDAR sensors are used to measure distances by transmitting pulses of near-infrared light to targets and measuring the time until the reflected pulses are detected by the sensor. Unlike image-based photogrammetry, LiDAR is capable of penetrating vegetation canopies and acquiring three dimensional information of the structure and composition of natural and anthropogenic surfaces by exploiting structural features and backscatter intensity profiles. While the use of active sensors such as LiDAR is now common in conventional manned airborne surveys, their integration with RPAS has remained challenging due to the trade-offs between performance and the weight, size or cost of these sensors. However, LiDAR sensors have recently been integrated on fixed-wing and rotary-wing platforms as turn-key solutions (e.g., Phoenix Aerial Systems). These sensors have been miniaturized to a point where they can fit most rotary-wing small RPAS (Table 11). The costs of some of these sensors have come down dramatically (e.g., Velodyne VLP16; $8,000 USD; March 2016). There is limited information available on the use of these RPAS-specific LiDAR sensors for civilian applications as they have only recently moved beyond the scientific proof-of-concept phase. From system specifications it appears that there is a range of capabilities (Table 11), but that due to their limited range the recommended scanning height falls between 20 – 60 m above ground-level.

Table 11: Overview of LiDAR Sensors Offered in Operational RPAS Platforms.

Manufacturer	Model	Frequency (p/sec)	Accuracy / Precision (mm)	Range (m)	Weight (kg)
Riegl	VUX-1 High Accuracy	1,000,000	5 / 3	400	5.4
Riegl	VUX-1 UAV	500,000	10 / 5	920	5.4
Riegl	VUX-1 Long Range	750,000	15 / 10	1350	5.4
Velodyne	HDL32E	700,000	20	120	3.2
Velodyne	VLP16	300,000	30	120	2.5
YellowScan	Mapper	40,000	150 / 100	-	2.1
YellowScan	Surveyor	300,000	50 / 30	-	1.5

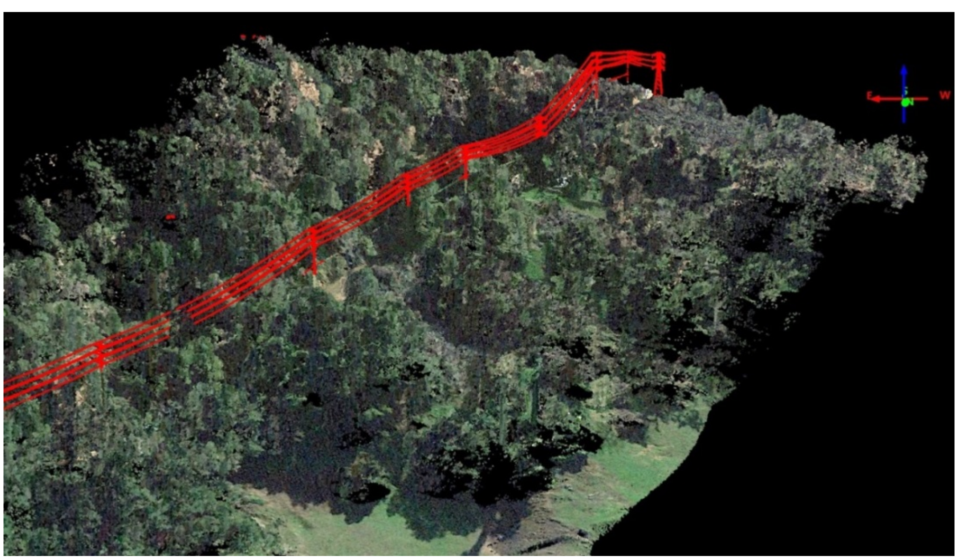

Figure 2: Power-line survey with a RPAS-based Velodyne HDL-32E LiDAR sensor (Phoenix Aerial Systems).

4.1.3.2. Synthetic Aperture RADAR (SAR)

Satellite-based and manned aircraft based Synthetic Aperture RADAR (SAR) sensors are well established within the remote sensing discipline, whereby they offer all-weather and day-or-night sensing capabilities. SAR sensors expose surface objects to distinct microwave frequencies and polarizations and measure the back-scatter that is returned. The back-scattering properties can be used to distinguish features on the ground and map changes over time by monitoring different geophysical and biophysical parameters. SAR applications include monitoring maritime activities (e.g., ships, icebergs, oil spills), digital elevation model production, subsidence mapping, feature detection under foliage, among others. The integration of SAR sensors into RPAS has faced similar challenges as LiDAR sensors with respect to the compromise between performance, weight, and costs. Small SAR sensors are generally still in the development phase, and no published case studies are available for specific operational applications (Colomina & Molina 2014; Whitehead & Hugenholtz 2014). Although a wide variety of RPAS-based SAR sensors have been proposed in the scientific literature (Pajares 2015) they are either not (yet) commercially available as turn-key solutions or fall outside of the scope of small RPAS operations due to their weight (e.g., > 25 kg). The only operational turn-key solutions that met the scope of this technology scan was IMSAR's NanoSAR-C (IMSAR 2016) and ARTEMIS MicroASAR (Edwards et al. 2008). The NanoSAR-c is a 1 kg sensor that was successfully integrated into a Boeing Insitu Scaneagle (The Boeing Company 2008), and can acquire backscatter images at KU-, L-, X-, and Ultra-wideband frequencies and at range resolutions between 0.3 m and 10 m. The MicroASAR is a 2.5 kg sensor that captures C-band frequency images at a 1.25 m maximum spatial resolution (Edwards et al. 2008; ARTEMIS 2016). Although the specifications of these sensors meet the payload capabilities of small RPAS, there is limited information and case studies available with respect to the use of these sensors for civilian applications. This indicates that most sensors are still in the development phase or are marketed towards military markets. Nevertheless, the civilian application of these sensors holds a considerable potential for the future.

4.2. Platforms Available Within the <25 kg RPAS Category

4.2.1. General Considerations

Beyond the classification of RPAS by size and weight (Table 4) platforms are generally differentiated by flight characteristics. Here the main division of interest is between fixed-wing and rotary-wing platforms, with large differences between their capabilities and performance (Table 12). Fixed-wing aircraft come in a range of different shapes (conventional, flying-wing) and configurations (propulsion at the front or rear) for system performance, but in general they can be characterized as being capable of flight using wings that generate lift caused by the vehicle's forward speed (thrust). Because they exhibit an efficient aerodynamic design and natural gliding capabilities (e.g., when thrust disappears) they are capable of long flight durations at high airspeeds enabling large survey areas per flight. Fixed-wing platforms also have a simpler structure composed of fewer parts, therefore increasing reliability and reducing the complexity of maintenance and repair. Two disadvantages of fixed-wing platforms are a direct result of a need for continuous forward motion to generate lift, as they require a larger operational footprint (i.e. larger take-off and landing site) and they cannot complete stationary work (e.g., inspections).

Rotary wing aircraft also come in a range of different shapes and configurations, but in general can be characterized by their use of rotors (two blades attached to a fixed, spinning mast) that spin continuously to produce the required airflow to generate lift. Rotary platforms can feature a conventional single-main rotor design (i.e., helicopter) or a design with four rotors (i.e., quadcopter), although designs with six rotors (hexacopter), and eight rotors (octocopter) are also widely available. As rotary aircraft do not require forward movement to generate lift, their biggest advantage is the ability for vertical take-off and landing (VTOL). This capability increases the functionality in rugged terrain by reducing the operational footprint considerably, and allows for applications that require stationary or slow-moving flights (e.g., single feature of interest being monitored for extended periods). The slower cruise speeds enables the acquisition of much higher spatial resolution imagery (e.g., 0.006 m; Mancini et al. 2013) compared to fixed-wing RPAS (e.g., usually 3-6 cm). Increasing the number of rotors on the aircraft generally increases the maximum payload weight, increases the stability of the platform in strong winds, increases the agility for precise maneuvering, and increases propulsion redundancy in case a rotor fails. Rotary aircraft do not have natural gliding capabilities and are aerodynamically less efficient than fixed-wing aircraft, and as a result they have a lower flight endurance and cruise speed which limits the maximum area coverage per flight. They also involve greater system complexity which translates into more complicated maintenance and repair processes, reducing operational time.

Table 12: General summary of operational constraints and considerations when choosing RPAS platforms.

Capability	Aircraft Type	
	Fixed-wing	**Rotary Wing**
Endurance	High	Low - medium
Payload capability	Medium	High
Stability	Medium	High
Ability to fly in wind	Medium	High
Operational footprint	Medium - High	Small - Medium
Take-off capability	Hand launch, catapult	VTOL
Landing capability	Open area belly landing, parachute	VTOL
Velocity/trust failure	Glide capability, parachute, controlled belly landing	Crash if rotors are not redundant
Stationary monitoring	No	Yes
Maintenance complexity	Low	Medium- High

4.2.2. North American Availability of Operational RPAS

The Canadian and United States market of small RPAS is highly diverse, with over 46 manufacturers producing 118 platforms capable of performing geomatics-related missions (Appendix 1). In terms of their capabilities, the available RPAS have wide ranging maximum take-off weights (0.7 kg to 25 kg), endurance (10 min to 24 hours), payload (0.2 kg to 15 kg), reported wind tolerances (28 km/h to 96 km/h), and reported minimum temperature tolerances (-60°C to -5°C). The majority of RPAS options offer multiple sensors as part of an integrated package. The costs of the platforms relate to these wide ranging capabilities as well as quality grades (e.g., consumer, commercial, industrial, military-grade), and ranges between $825 CAD to $600,000 CAD.

Distinct patterns in capabilities emerge when the available platforms were grouped and averaged by aircraft type (Table 13). Even though rotary wing and fixed-wing aircraft have similar maximum take-off weights, in general fixed-wing aircraft have a lower payload capacity (1 kg versus 2 kg, respectively). Fixed-wing aircraft are capable of longer flight times (median = 90 min) than rotary wing aircraft (median = 30 min), and are generally more expensive than rotary wing aircraft ($46k versus $19k). Both aircraft types feature similar reported wind and minimum temperature tolerances at a group average. Because these metrics were self-reported by the manufacturers they likely represent ideal conditions, and thus heavier payloads, faster wind speeds, and lower temperatures will reduce the performance of RPAS.

Table 13: General RPAS Market Comparisons.

Capability	**Average small RPAS** [1,2]		
	Total Market (n=118)	**Fixed-wing (n=45)**	**Rotary Wing (n=72)**
Maximum take-off weight (kg)	5.3	5.3	6.0
Endurance (min)	40	90	25
Electric vs. gas (n)	113 vs. 5	44 vs. 1	69 vs. 3
Payload capacity (kg)	1.5	1.0	1.8
Wind tolerance (km/h)	48	60	41
Minimum temperature (°C)	-10	-10	-10
Medium price (CAD)	25,400	48,000	20,000

[1] The median (middle score) was used as measure of central tendency due to the skewness of the data.
[2] One RPAS model (AeroVelco Flexrotor) was excluded as this is a hybrid VTOL fixed-wing aircraft.

The available rotary-wing and fixed-wing RPAS have similar distributions of maximum take-off weight, which highlight the wide range of options available for organizations to integrate RPAS in their programs and services (Figure 3). Despite these similarities there are limited options available for fixed-wing aircraft beyond 10 kg maximum take-off weight (MTOW), which is a result of market trends that follow current aviation regulations and a focus on local applications. For example, those fixed-wing platforms that exceed 10 kg MTOW (e.g., Brican TD100, Insitu ScanEagle) are focused on the industrial and military market segments where longer ranges and larger payloads are required.

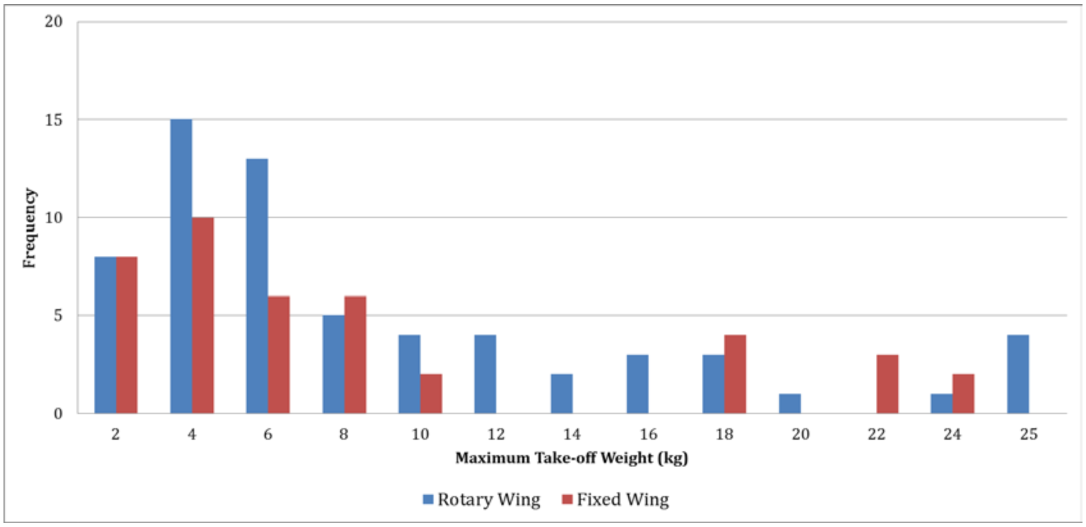

Figure 3: Distribution of maximum take-off weight for rotary wings and fixed-wing RPAS.

The variation in endurance is smaller for rotary-wing aircraft than that of fixed-wing aircraft (Figure 4). The distributions highlight the physical limitations of the rotary-wing design, whereby gas powered engines are required to further increase the range of these types of platforms (e.g., Flint Hill Solutions 520/620). Most rotary-wing platforms can fly for 20 min to 30 min, whereas most readily available consumer- and- commercial fixed-wing platforms can stay aloft for 50 min to 90 min. These findings highlight the large differences in spatial coverage that can be expected.

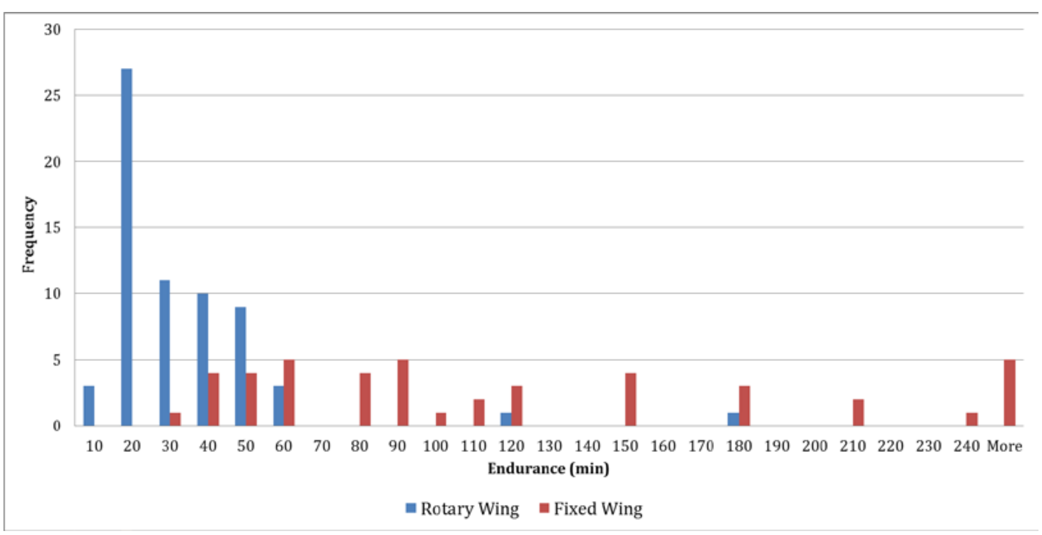

Figure 4: Distribution of endurance for rotary wings and fixed-wing RPAS.

The available rotary-wing and fixed-wing RPAS have similar distributions of maximum payload weight, which highlight the wide range of options available for organizations to integrate RPAS in their programs and services (Figure 5). Most platforms support payloads up to 1 kg, although rotary-wing platforms provide a greater range of options for specific application needs. Rotary-wing aircraft are capable of carrying twice the maximum payload weight compared to fixed-wing platforms, however due to the skewed distribution the median averages (i.e., 1 kg vs. 2 kg) are more reflective of the market than the arithmetic mean (i.e., 1.8 kg vs. 3.4 kg) due to outliers.

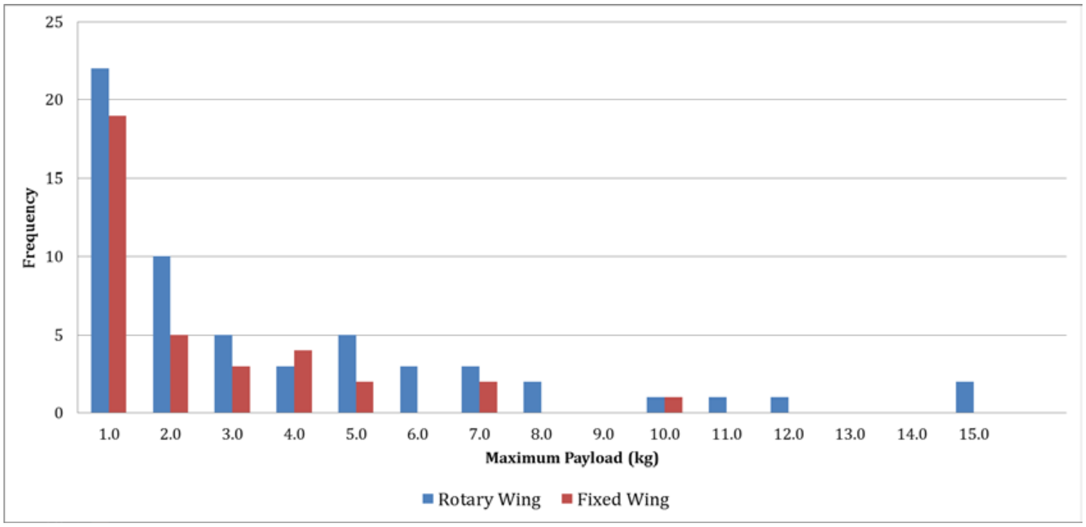

Figure 5: Distribution of maximum payload for rotary wings and fixed-wing RPAS.

The distribution of wind tolerances is highly variable among RPAS platforms (Figure 6). Almost half of the manufacturers did not provide this information (Appendix 1) and it is likely that other manufacturers reported tolerances that do not reflect what can be reasonably expected at the operational level. For example, manufacturer-reported tolerances generally range between 40 km/h to 60 km/h, even though more practical tolerances range between 14 km/h to 35 km/h (Rosnell & Honkavaara 2012; Honkavaara et al. 2013; Barry & Coakley 2013; Puliti et al. 2015).

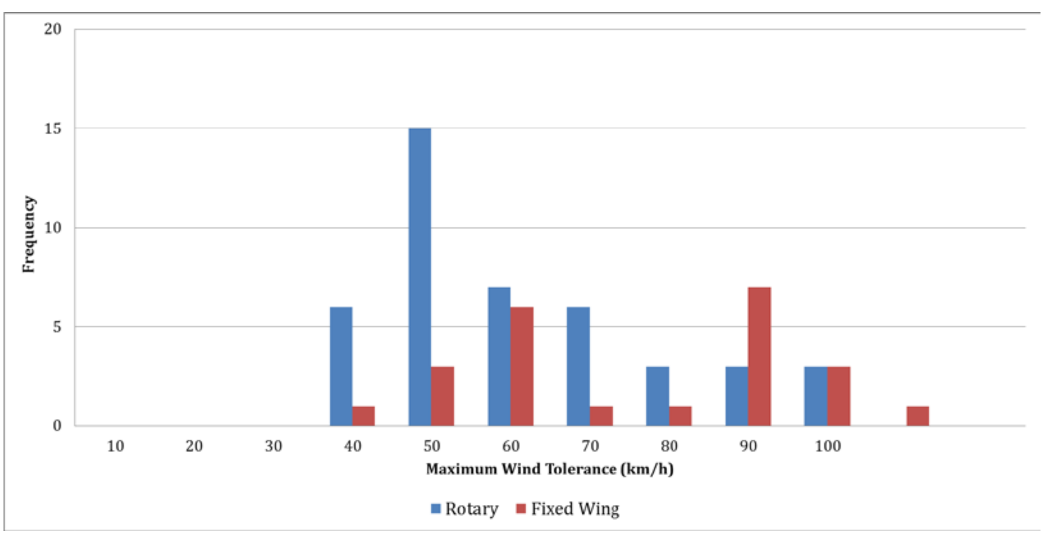

Figure 6: Distribution of maximum wind tolerance for rotary wings and fixed-wing RPAS.

The available rotary-wing and fixed-wing RPAS have similar distributions of minimum operating temperatures, which generally range between -5°C and -20°C (Figure 7). There are no standardized tests to report these tolerances, and they likely stem from observations in the field. Even in cases where the minimum operating temperature of a platform is rated at below-freezing temperatures (e.g., Sensefly eBee: -10°C), low temperatures (e.g., 0 °C) increase battery consumption and shorten flights (Puliti et al. 2015). Operations at these temperatures are therefore greatly constrained whereby endurance estimates cannot be upheld for battery-powered systems (Figure 4).

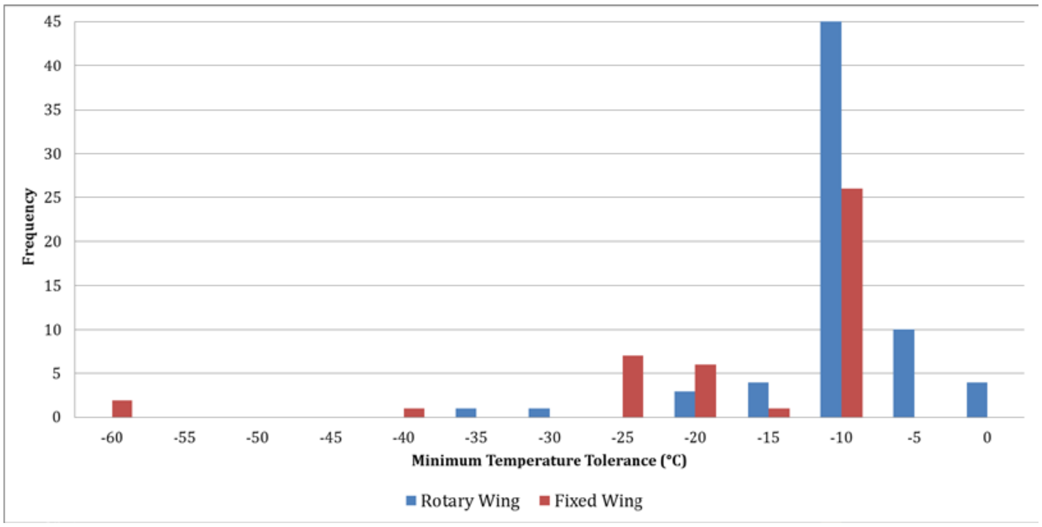

Figure 7: Distribution of minimum temperature tolerance for rotary wings and fixed-wing RPAS.

Rotary-wing and fixed-wing RPAS do not have similar distributions of platform investment costs (Figure 8). The bi-modal distribution of rotary-wing costs relate to differences in market segments, whereby numerous platforms are available for less than $5,000 or in the $40,000 range. Fixed-wing platforms are generally more expensive, especially those focused on industrial applications. Rotary-wing platforms represent low-cost options to demonstrate a range of solutions. RPAS therefore represent an avenue to acquire data that can meet any organizational budget.

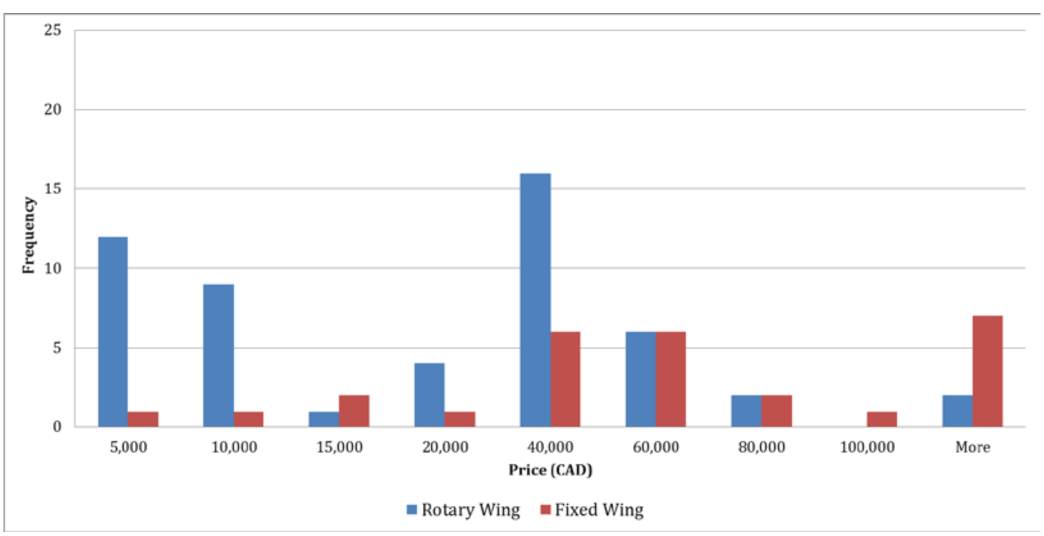

Figure 8: Distribution of platform investment costs for rotary wings and fixed-wing RPAS.

4.3. Image Processing for RPAS Mapping

4.3.1. Concepts

As with conventional manned airborne surveys, data processing is a key step in the development of photogrammetric and remote sensing services. The concepts between processing data acquired through manned airborne surveys and RPAS are similar (e.g., flight lines, conjugate points, interior and exterior orientation, collinearity equations) as well as the derived end-products (e.g., ortho-mosaic, elevation models). However, there are key differences with respect to the production methods that are relevant for operational services as they affect levels of automation and choice of software packages (Table 14; Fonstad et al. 2013; Colomina & Molina 2014).

Conventional photogrammetric triangulation is continually evolving but typically relies on strips of overlapping images acquired by metric cameras with stable interior orientation and distortions, and acquired in a rigid and regular flight block structure (nadir images, constant scale and overlap)(Linder 2009). To obtain three dimensional coordinates of objects, the interior, absolute, and relative orientation of the imagery must be determined. The interior orientation of metric cameras is solved through camera calibration. The absolute orientation is derived by first manually identifying GCPs for each flight line (or by obtaining the X,Y,Z coordinates along with three rotational angles from the GNSS and IMU telemetry). Afterwards the position and orientation of each pixel is determined through automatic aerial triangulation (AAT) that solves the collinearity equations (also referred to as bundle block adjustment). Subsequently the relative orientation is determined by identifying common points (i.e., conjugate points) between the overlapping regions through cross-correlation or other image matching techniques. Parallactic angles are determined by matching corresponding points, from which elevation values are calculated.

The imagery acquired through RPAS typically does not meet the assumptions required for conventional photogrammetry (Colomina & Molina 2014). The images are acquired by non-metric consumer-grade cameras that are un-calibrated (i.e., no knowledge on the principal point, radial distortion, focal length, accurate altitude) and whereby flight lines are not structured in a regularly-spaced, rigid (or systematic) way (i.e., sometimes random). So-called Structure-from-Motion (SfM) techniques are similar to conventional photogrammetry in that they both use triangulation of corresponding points in overlapping images to reconstruct a three-dimensional scene. However, there are two major differences in the image processing pipeline (Fonstad et al. 2013). First, the sometimes randomly orientated images at varying scales challenge cross-correlation techniques of conventional photogrammetry. This challenge is solved by an automated image matching algorithm that is scale-independent (e.g., SIFT, SURF) and that can recognize common points in multiple images despite large changes in image scale and view-point. Second, conventional photogrammetry requires ground control points to solve the collinearity equations and obtain a three-dimensional reconstruction. In contrast, the SfM technique acquires the scene reconstruction (i.e., a 3D point-cloud) by solving the collinearity equations in an arbitrarily scaled coordinate system using the large number of common points generated through SIFT. This intermediate reconstruction is then projected to real-world coordinates using ground control points visible in the point-cloud, or by using exterior information derived by the GNSS and IMU telemetry data.

Table 14: Generalized comparison between conventional photogrammetry and Structure-from-Motion.

Characteristics	Image Processing Technique [1]	
	Conventional Photogrammetry	**Structure From Motion**
Flight-lines	Rigid, rigorous flight-lines	Structured or unstructured flight-lines (random)
Sensor	Metric, calibrated cameras	Non-metric, un-calibrated cameras
Conjugate Points Method	Cross-correlation on absolute values or other image matching technique	A scale invariant feature algorithm based on brightness gradients
Sensitivity of Method	Sensitive to changes in image scale	Not sensitive to changes in image scale and viewpoint
Collinearity Solutions	*After* the user provides GCPs or GNSS/IMU telemetry	*Before* the user provides GCPs or GNSS/IMU telemetry
Basis for accuracy	Small number (<100) of highly accurate GCPs and camera points	Large number (> 1000) of conjugate points and a few GCPs (0-20)

[1] After Fonstad et al. (2013).

4.3.2. Software Applications

The vast majority of RPAS imagery for mapping is processed using software packages based on photogrammetric techniques and field-measured GCPs (Colomina & Molina 2014). Due to the low availability and cost of carrier-phase GNSS systems and accurate IMUs, direct georeferencing using highly accurate integrated sensor orientations (e.g., PPK or RTK) is not yet widely practiced. There is a wide variety of software solutions available for RPAS mapping missions which use sophisticated algorithms to compensate for the non-rigid flight-lines and lower quality cameras. There are three general categories of photogrammetric software available: 1) conventional photogrammetric packages updated for RPAS, 2) SfM-based software specifically designed for RPAS, and 3) cloud-based SfM solutions.

Conventional photogrammetric packages, such as *BAE Systems Socet Set, Trimble Inpho, Leica LPS,* and *Hexagon IMAGINE Photogrammetry* have been used to process RPAS imagery. These conventional, long-established and proven software packages were not designed to process RPAS image blocks as a turn-key solution. To resolve this they are typically used in the latter part of the image processing pipeline after a SfM-based algorithm determined initial orientations and a surface model as input for subsequent processing (Laliberte et al. 2011; Rosnell & Honkavaara 2012; Cramer 2013; Haala et al. 2013). If used as stand-alone turn-key software, the AAT process is typically run two or three times to produce the best results (Whitehead et al. 2013; Hugenholtz et al. 2013; Whitehead et al. 2014). During these iterations, the first triangulation process includes all the GCPs to provide the best overall adjustment, after which the second triangulation process would be conducted with a self-calibration process to create a lens distortion correction grid that is used to minimize the residuals. The final triangulation process would subsequently be conducted with an evenly distributed subset of GCPS to allow for independent check points. These software packages consist of user-friendly interfaces and semi-automatic processing pipelines, and provide intermediate quality-control checks and interactive editing tools. However, the performance of these conventional software packages can break down in case of insufficient overlap or large changes in image scale (Rosnell & Honkavaara 2012; Gini et al. 2013; Wiseman & van der Sluijs 2015), and the need for multiple iterations of pre-processing requires greater manual interactions.

In contrast, SfM-based photogrammetric software packages such as *Pix4D Mapper Pro, Agisoft Photoscan Professional, SimActive Correlator 3D, Menci APS, MosaicMill EncoMosaic, ENVI/ICAROS OneButton,* and *Trimble UASMaster* have been specifically engineered to accept RPAS images. These packages are straight-forward to operate as they are capable of fully automatic data processing with limited user interaction, but because of this black-box approach they may have limited capabilities with respect to self-diagnosis and intermediate quality control checks. The above-mentioned packages include camera self-calibration techniques, and the irregularity of image blocks does not form a problem for most automatic image matching and aerial triangulation (Figure 9). These software packages have led to a "new" mapping community relative to the "old" photogrammetric community (Colomina & Molina 2014), where the performance and user-friendliness of the older "evolved" software packages and new "revolutionary" packages continues to be scrutinized. Both software types can obtain similar accuracies (Cramer 2013; Colomina & Molina 2014) whereby the main product differences revolve around the level of required user interaction, post-process editing functions, processing time, and costs. There is therefore room for multiple vendors to become market leaders with their respective value propositions.

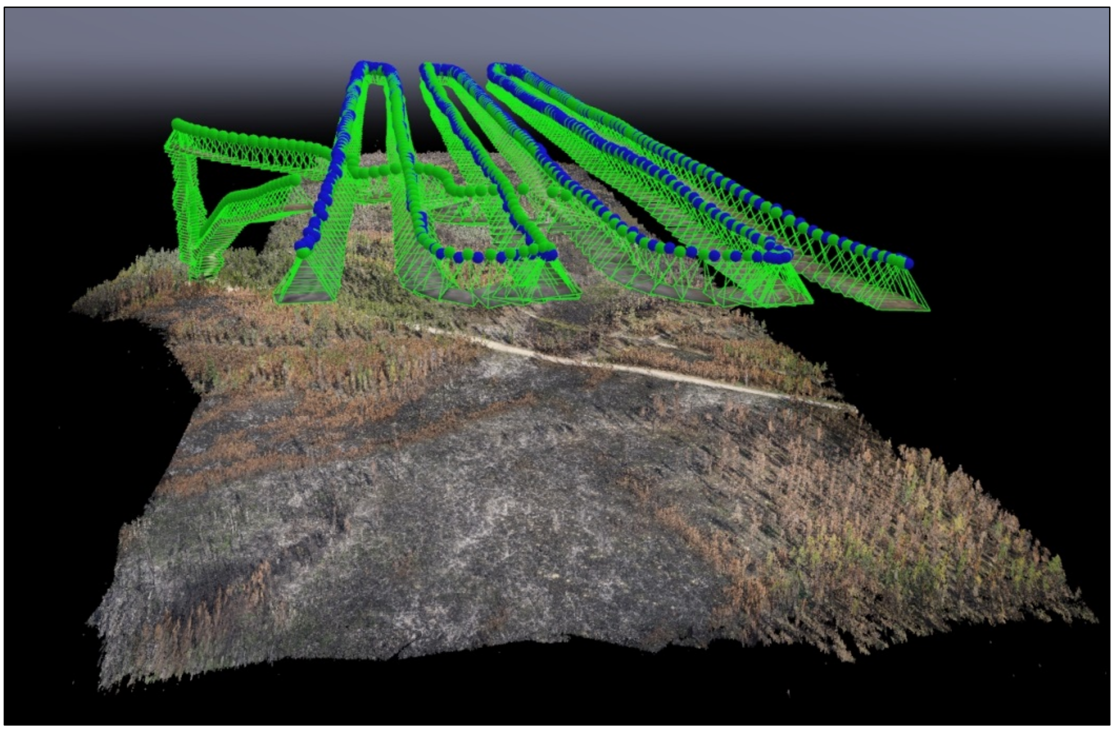

Figure 9: RPAS data processing in a SfM software package for forest fire burn severity mapping. Note the successful scene reconstruction based on individual images acquired at a range of altitudes and image orientations during the take-off, cruise, and landing phase of the mission (illustration only; images are typically restricted to cruise altitude only).

A considerable hardware and software investment may be required if a RPAS program is based on processing data on local infrastructure, and this is especially the case if an organization does not already have licenses to conventional photogrammetric setups. For example, *Pix4D* and *Agisoft* generally recommend advanced configurations with a 6- to 8-core CPU, 32-64 GB RAM, 256-512 GB SSD, and a 2-4 GB GPU. These configurations typically cost $2,000 - $6,000 CAD excluding the software ($3,500 - $8,700 USD; March 2016; not including annual maintenance fees). To lower the barrier of entry, *Pix4D* also offers monthly and annual rental options ($350 USD/month, $3,500 USD/year; March 2016). In any case, a one-time hardware and software investment of $6,700 to $17,500 CAD (March 2016 currency exchange) is required depending on the requirements of the RPAS application (e.g., image resolution, turn-around time). These costs may challenge the integration of RPAS to meet organizational mandates if mapping information is required.

In addition to software run on local infrastructure, RPAS cloud solutions such as *DroneDeploy*, *Dronemapper*, *Datamapper*, *3DR Site Scan*, *Autodesk ReCap 360*, *MapsMadeEasy*, and *Hexagon Geospatial GeoApp.UAS*, lighten the burden of up-front investments through monthly or pay-per-use payment models. Online data processing approaches are black-box SfM solutions whereby users upload raw RPAS imagery and receive downloadable mapping products in return. Pay-per-use pricing typically depend on the size of the survey area, sensor size, image overlap, and desired spatial resolution, whereas unlimited data processing options based on monthly pricing models are currently $499 USD/month (*DroneDeploy*, *3DR Site Scan*; March 2016). At these prices the break-even point between local- and cloud-based solutions is roughly between 10 and 26 months depending on the software and hardware solution chosen. Data processing using cloud solutions is often completed post-flight as a separate service, however, vertically-integrated app- and cloud-based solutions have recently appeared on the market. For example, *DroneDeploy* is a cloud-based solution for automated flight planning and flight execution, whereby data can be processed post-flight or in real-time in case the RPAS has a cellular LTE module. Similarly, *3DR Site Scan* offers a complete solution whereby flight planning, data processing, and data visualization in Autodesk products (e.g., AutoCAD, Civil3D) are seamlessly integrated.

Intermediate solutions that are situated between pure desktop- and cloud- solutions consist of distributed computing capabilities that access the underutilized power of computers in a Local Area Network. In these situations multiple software instances running on different computers can work on the same task in parallel, which reduces the overall processing time. Software programs such as *Agisoft Photoscan Professional* are compatible with this type of data processing (Agisoft LLC 2016). Berkley Open Infrastructure Network Computing (BOINC) is a well-known example of an open-source "middle-ware" solution within the broader environmental modeling discipline, where organizations can set up their own distributed computing system. However, these solutions require manual setup and may not be compatible with SfM-based photogrammetric software packages.

5. RPAS REGULATORY OVERVIEW

In addition to operating RPAS in sometimes harsh Canadian environmental conditions, RPAS must operate within regulations and within socially acceptable means. In Canada, the operation of RPAS falls under the Aeronautics Act and the Canadian Aviation Regulations, which are administered by Transport Canada. Transport Canada has developed specific regulations and guidelines that govern the operation of RPAS in addition to (safety) regulations governing the operation of manned aircraft that also apply to RPAS use. RPAS operators must also comply with the Criminal Code of Canada and provincial/territorial and municipal regulations with respect to trespassing and privacy. The following section provides an overview of the regulations that must be adhered to for operational use of RPAS.

5.1. Aviation Regulations

The regulations enacted by Transport Canada apply to all activities in non-military airspace, including commercial applications, government use, scientific research, and search-and-rescue, whereby use of RPAS is governed to an equivalent level of safety as manned aircraft. To carry out non-recreational geomatics-related missions, an individual must hold aircraft specific third-party liability insurance (≥ $ 100,000 coverage) and pursue one out of two possible avenues to fly RPAS:

1. Obtain a Special Flight Operation Certificate (SFOC), or
2. Operate under an "Exemption from a SFOC" if the aircraft weighs less than 25 kg and is operated within line-of-sight (< 1 km) and 5 nm (9 km) from built-up areas, airports, fires.

5.1.1. Special Flight Operation Certificate (SFOC)

The application for SFOCs is the only recognized process for the legal non-recreational operation of RPAS in Canada if the proposed mission cannot meet the Exemption conditions (Section 5.1.2). All initial applications for SFOCs require detailed information on the personnel, RPAS, and mission plan to receive approval (Table 15), and must follow the Transport Canada (2014d) Staff Instruction SI 623-001. These instructions clarify that RPAS operators do not have an automatic right to airspace use and they must integrate safely with other airspace users. The SFOC process requires operators to analyze the risk of the proposed mission and establish safety provisions. The proposed operation will not be approved if safety provisions are not be made or if operations negatively impact the safety of other airspace users.

Table 15: Required information for a SFOC application (Transport Canada 2014d)..

Personnel	RPAS	Mission plan
Applicants' Name, address, and telephone number	Description of the aircraft	The type and purpose of the operation
Operation Managers' name, address, and telephone number	Description of the ground control station	Dates, alternate dates, and times of the proposed flight
Method(s) of contact during the operation	Description of communication links and risks of interference	Security plans for area of operation
Ground Supervisors' name, address, and telephone number	Description of voice communications	Emergency contingency plan
	Description of payload(s)	Detailed operational plan

For new RPAS operators each mission will require its own SFOC whereby the applicant has to develop detailed plans to mitigate the risks of: 1) collision with other aircraft and persons and property on the ground, 2) impacts of inclement weather/icing, 3) lost link scenarios, 4) diversions, or 5) flight termination. The Staff Instructions highlight four specific SFOC application categories, of which three are applicable to commercial operations (Table 16). Each of these categories has a standardized process to provide the required information to Transport Canada. Due to the high volume of applications, expedited SFOC options exist that use predetermined check-lists for lower risk operations (e.g., Transport Canada - Prairie and Northern Region). Once submitted, Transport Canada Inspectors are responsible for reviewing SFOC applications according to the Staff Instruction. When approved these initial SFOCs are limited to a validity period wherein the single operation can be conducted. Although operators must submit a SFOC application at least 20 working days prior to the date of the proposed operation (according to the Staff Instruction), an analysis of SFOC applications has indicated that the average time to SFOC approval was 22.9 days in 2012 (the last year of available data; Thompson & Saulnier 2015).

Table 16: Categories of commercial SFOC applications.

Type	Description
Restricted Operator Simplified	▪ Operators: unable or unwilling to become a compliant operator, or compliance to those criteria are not required. ▪ Permissions: granted fewer privileges than compliant operators. ▪ Operations: include small RPAS operating within visual-line-of-sight conducting pilot training or aerial work (aerial photography, aerial inspections). ▪ Operational requirements: a single make/model, a single control station, a single RPAS in flight, a single pilot in control, a maximum altitude of 300 ft. (90 m) AGL*, more than 100 ft. distance from persons not associated with the operation, uncontrolled (class G) airspace only, more than 3 nautical miles (5 km) from airports, a maximum airspeed of 87 knots.
Restricted Operator Complex	▪ Operators: unable or unwilling to become a compliant operator, or compliance to those criteria are not required. ▪ Permissions: granted fewer privileges than compliant operators. ▪ Operations: large RPAS (≥ 25 kg), BVLOS** operations; foreign RPAS operators; or RPAS operating in Class F Restricted airspace. ▪ Operational requirements: as specified in the SFOC.
Compliant Operator	▪ Operators: are required to demonstrate that they have a compliant organization with compliant personnel operating a compliant small RPAS within visual-line-of-sight. ▪ Permissions: granted greater geographical validity, operations in built-up areas, longer validation periods, more streamlined and prioritized SFOC renewals. ▪ Operations: include small RPAS operating within visual-line-of-sight during the day/night ▪ Operational requirements: requires documentation such as an Operations Manual, Standard Operating Procedures, Training Manual, RPAS flight manual, RPAS maintenance manual, Declaration of compliance, Statement of conformity.

Source: (Transport Canada 2014d). * AGL: above ground level. ** BVLOS: beyond visual line-of-sight.

Once a RPAS operator has demonstrated sufficient experience and a history of safe operations they are eligible to apply for a SFOC under the Compliant Operator category, which provides greater mission flexibility and privileges (Table 16). Due to the risk associated with operations in built-up areas, the Staff Instructions indicate that only compliant operators may operate in these environments (or under the expedited SFOC Option 2 in the Prairie and Northern Region). Operators must conduct a site survey and establish candidate landing areas.

Experienced operators can also file for long-term certificates that allow multiple operations over an extended timeframe and within a specified geographical area (e.g., municipality, province, multi-province) without the need to apply for a SFOC on a project-by-project basis. Previously known as “blanket” SFOCs, these long-term certificates are now referred to as “standing” SFOCs, and allow for greater operational flexibility as risk evaluation and management processes have been established by the operator and approved by Transport Canada. Both restricted and compliant operators can apply for standing SFOC’s that are valid between one and three years, respectively.

SFOCs are issued with a list of general and specific conditions regarding the operation, flight, personnel, system condition, and incident reporting, which ensure that RPAS operators comply with the CAR regulations. SFOCs can be suspended or cancelled at any time if operators are not in compliance to the SFOC and the provisions. Transport Canada can issue fines of up to $5,000 for an individual and $25,000 for a corporation if an operator conducts a RPAS mission when a SFOC is required. Transport Canada can also issue fines of up to $3,000 for an individual and $15,000 for a corporation if the operator fails to comply with the conditions laid out in the SFOC.

Beyond the need for a SFOC the Transport Canada (2014d) Staff Instructions require RPAS operators to obtain a Restricted Operator Certificate–Aeronautical (ROC-A) from Industry Canada. The purpose of the ROC-A requirement is to ensure that RPAS operators are sufficiently proficient in operating radiotelephone equipment to contact other aircraft or Air Traffic Control and possess a general knowledge of operating procedures and regulations relating to radiotelephones (e.g., the Canadian Radiocommunications Act). A ROC-A study course and exam is generally provided through a UAS ground school course (Section 5.1.4), or can be completed through self-study and an examination with an accredited examiner (Industry Canada 2015).

5.1.2. Exemptions from SFOC

New regulations adopted on November 26, 2014 have established an exemption from SFOC requirements for non-recreational applications of RPAS under 25 kg (Transport Canada 2014a). Although this exemption removes the need to formally apply for a SFOC, it does not remove the restrictions and documentation requirements to conduct missions (Figure 10). RPAS operators of aircraft under 2 kg must adhere to 37 conditions, including an 18-year age minimum, obtaining sufficient liability insurance (≥ $100,000), and operational restrictions. Under this exemption, RPAS missions are permitted when conducted with visual-line-of-sight, during daylight, at a maximum altitude of 300 ft. (90 m), at a minimum of 5 nautical miles (9 km) from airports and built-up areas, and at a minimum of 100 ft. (30 m) lateral distance to people and structure.

For operators of RPAS weighing between 2 kg and 25 kg a total of 58 conditions must be adhered to, whereby these conditions further expand on the conditions of the sub-2kg exemption (Table 17). This exemption includes the requirement to notify Transport Canada in writing through an online webpage (Transport Canada 2015a) and the successful completion of a self-study or pilot ground school course offered through a service provider. These exemptions will be in effect until December 21, 2016 but will be extended until new RPAS regulations are published in spring 2017 (Transport Canada 2016)(Section 5.1.3). If conditions cannot be met a SFOC must be obtained.

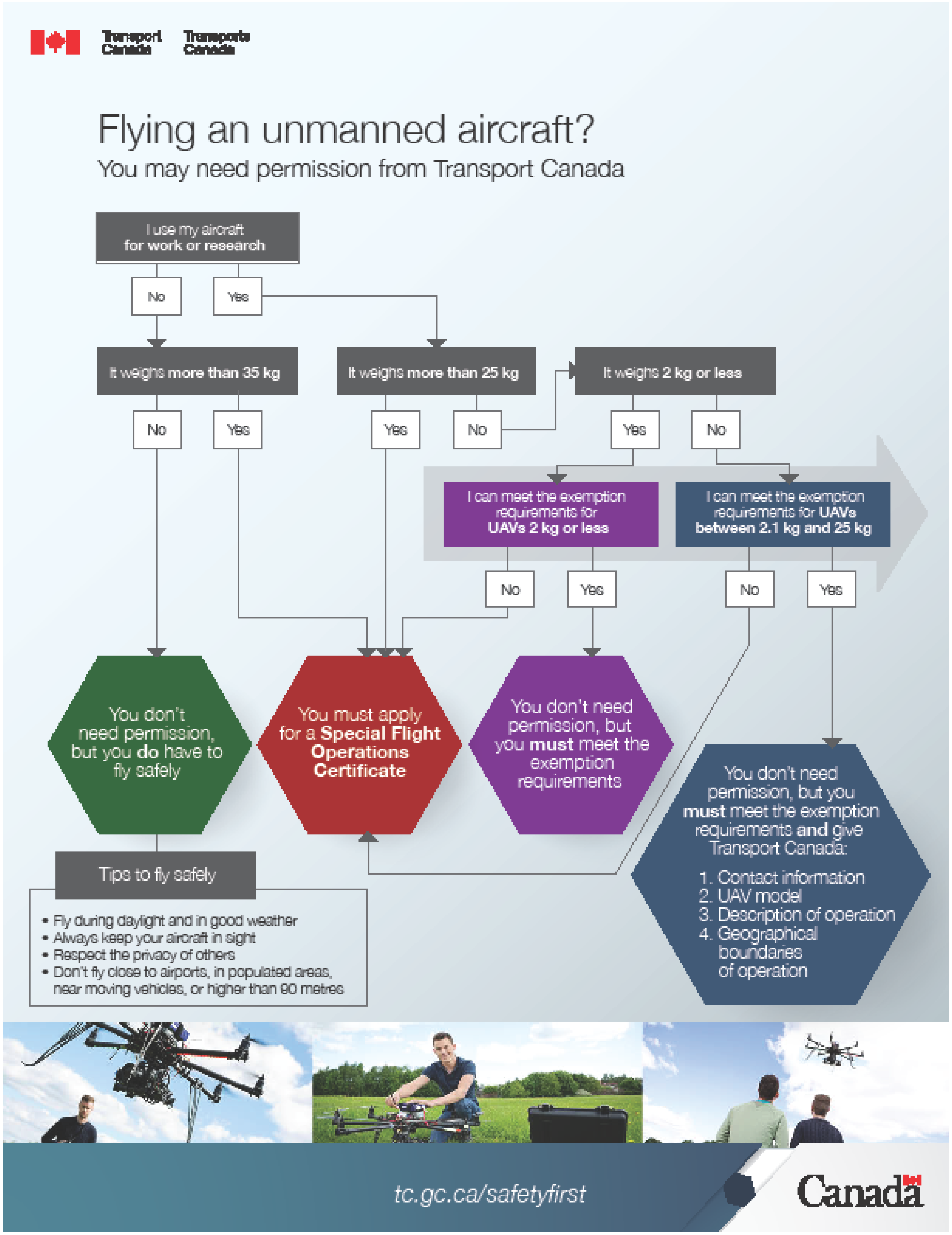

Figure 10: Flowchart highlighting the permission to conduct a RPAS mission (Transport Canada 2014b).

Table 17: A summary of additional conditions stipulated by the Exemption of SFOC (2 kg – 25 kg).

Category	**Additional Conditions**[1]
Lateral distance from buildings, structures, vehicles, vessels, animals, or persons	At least 500 ft. (150 m)
Lateral distance from general public, spectators, bystanders, or people not associated with operation	At least 500 ft. (150 m)
Establish and adhere to procedures to be followed in case control of RPAS cannot be maintained	Must establish procedures for: contacting emergency responders, landing/recovering the RPAS safely, contacting the appropriate air traffic service unit, an emergency contingency plan
Communication stipulations regarding take-off and landing	Shall not conduct a take-off/launch of a RPAS unless the risk involved with lost link circumstances has been assessed and a determination has been made as to when auto-recovery maneuvers or flight termination shall be initiated.
Stipulations regarding icing, frost, ice, or snow conditions	Shall not operate a RPAS in known or forecast icing conditions, or when the RPAS has frost, ice or snow on its critical surfaces.
Use of portable electronic device near ground control station	Shall not permit the use of a portable electronic device at the control station of a RPAS system where the device may impair the functioning of the systems or equipment.
Availability of operational and emergency equipment	Shall ensure the availability of checklists that enable a RPAS system to be operated in accordance with the manufacturer limitations and a hand-held fire extinguisher
Operator position relative to RPAS during take-off and landing	Shall remain clear of the take-off, approach and landing routes and the pattern of traffic formed by manned aircraft operating in the vicinity of aerodromes
Requirement for operator training	The pilot operating a RPAS system under this exemption shall have successfully completed a pilot ground school program
Requirements for RPAS system conditions and capabilities	Shall ensure prior to take-off that there is a means of: controlling the flight of the RPAS, monitoring the RPAS, navigation; communication, detecting hazardous l flight conditions, mitigating the risk of loss of control, sensing and avoiding other aircraft, remaining clear of cloud.
Requirements for inspecting and repairing damaged RPAS	Shall ensure that a RPAS is not flown if it has been subjected to any abnormal occurrence unless it has been inspected for damage and repaired, if needed to ensure safe operation.
Requirements for RPAS maintenance	Shall ensure that all maintenance and servicing are performed in accordance with the manufacturer's specifications.
Requirements to follow manufacturer directives regarding the safety of RPAS	Shall ensure that the requirements of any airworthiness directives, or equivalent, issued by the manufacturer have been completed.
Requirements for reporting RPAS operations	Shall, prior to the commencement of operations, notify Transport Canada through an online web-form
Requirements to report aviation occurrences to Transport Canada	Shall report injuries to any person requiring medical attention, unintended contact between a RPAS and persons, livestock, vehicles, vessels or other structures, unanticipated damage incurred to the airframe, control station, payload or command and control links, anytime the RPAS is not kept within the geographic boundaries and/or altitude limits, any collision or risk of collision with another aircraft, anytime the RPAS becomes uncontrollable, experiences a fly-away or is missing; and any other incident that results in a Canadian Aviation Daily Occurrence Report (CADORS).

[1] Summary of conditions. Refer to Transport Canada (2014a) for complete list of exemption requirements.

5.1.3. Proposed Amendments to RPAS Aviation Regulations

In 2015 Transport Canada released a Notice of Proposed Amendment (NPA) to establish a comprehensive regulatory framework for unmanned aircraft not exceeding 25 kg that are operated within visual-line-of-sight (Transport Canada 2015b). These proposed amendments indicated the regulatory approach Transport Canada intends to adopt after stakeholder consultations.

As proposed, the amended regulations include the adoption of standardized terminology (Section 1.3) and a risk-based approach based on the risk of RPAS being fatal to people on the ground, damaging property, and the risk that RPAS pose to other aircraft in-flight. The key factors of concern are: 1) the size of the aircraft, 2) its location, and 3) its operational complexity. Further, the NPA proposes distinct regulatory classes that remove the intent of the operation as the means of separating different sets of regulations (Table 18), whereby each class would have a distinct set of aircraft and pilot requirements, along with mission privileges (Table 19). As the amendments have not yet been finalized at the time of writing only a general overview of the requirements and privileges can be provided for awareness of the upcoming changes (Transport Canada 2016). The proposed requirements indicate that organizations meeting certain criteria require an "adequate management organization" that is made up of more formal flight operations, pilot training programs, maintenance procedures, standard operating procedures, and company operations manuals along with specifications for aircraft marking and registration (Transport Canada 2015b).

Table 18: Proposed RPAS classes as per the NPA (Transport Canada 2015b; Transport Canada 2016).

Operation	RPAS category	RPAS sub-category	Description	Operational Example*
Within visual line of sight	Low Threshold RPAS		Lowest risk category. Unlikely to result in fatalities on the ground. Likely based on a weight (e.g., 1 kg) or kinetic energy (≤ 12 J/m^2). Will cover most recreational activities and simple non-recreational applications	Use of sub-1kg aircraft in built-up area for inspections up to 300 ft. (90 m) altitude (but not near aerodromes or over people)
	Small RPAS	Limited operations	Next level of risk. Includes sub-25-kg aircraft that meet design criteria. Restricts use to rural/remote applications, away from airports	Use of 1-25 kg aircraft in rural area for agriculture, forestry, earthworks application
		Complex operations	Highest level of risk of sub-25kg systems. Operations permitted in built-up areas, over people, near aerodromes, at night. Most comprehensive requirements on pilot, procedures, design criteria	Use of 1-25 kg aircraft for earthworks application in built-up areas and near aerodromes
	Large RPAS	-	-	Use of > 25 kg aircraft for monitoring and mapping
Beyond line of sight	All UAS	-	-	-

* If Low threshold RPAS category is based on weight. Greyed-out blocks require the SFOC process. Operations with low threshold/small RPAS which cannot adhere to restrictions will also require a SFOC.

Table 19: Requirements and privileges of proposed RPAS classes.

	Low Threshold RPAS	Small RPAS (limited)	Small RPAS (complex)
	Aircraft Requirements		
Identification	✓	✓	
Marking and registration			✓
Design standard			✓
	Pilot Requirements		
Age restriction		✓	✓
Knowledge test	✓ (basic)	✓ (basic)	✓ (advanced)
Pilot permit			✓
Respect for privacy	✓	✓	✓
	Permissions to Fly		
Within 5 nm (9 km) of built-up area	✓		✓
Within 5 nm (9 km) of aerodrome			✓
Over people			✓
At night			✓
Liability insurance	✓	✓	✓
Operator certificate	✓	✓	✓
Maximum altitude	300 ft. (90 m)	300 ft. (90 m)	400 ft. (120 m)

After: Ellis (2015). Updated based on Transport Canada (2016).

5.1.4. Training

Training is a critical link in delivering the capabilities that RPAS offer in a safe, efficient, and effective way. Organizations can acquire the most advanced equipment, but if pilots are not properly trained on the equipment or do not have an understanding of the system components, the advantages offered by RPAS will be lost through misapplication. Several service providers are available across Canada (e.g., British Columbia, Alberta, Ontario, Quebec) who offer the required ground school course to apply for a SFOC or operate under the Exemption from SFOC 2-25 kg class (Unmanned Systems Canada 2015). These courses typically range between 1.5 to 3 days in length and $500-$1,000 in costs, although some providers include longer-term flight skills training in their offerings as well (Figures 11 and 12). Transport Canada has defined the requirements for course material (Transport Canada 2014c), although the NPA indicated that there is no intention to formally certify ground school courses. This is one of the reasons why self-study courses are permitted and are available online through service providers. In general, RPAS pilots should be able to demonstrate that they:

- understand airspace regulations, classification, structure, weather, Notice To Airmen (NOTAM) reporting, Air Traffic Control communications, and aeronautical charts;
- can plan safe missions within the parameters of the law and technological capabilities;
- can file SFOC applications;
- can safely conduct missions; and
- can perform in-field trouble-shooting and maintenance.

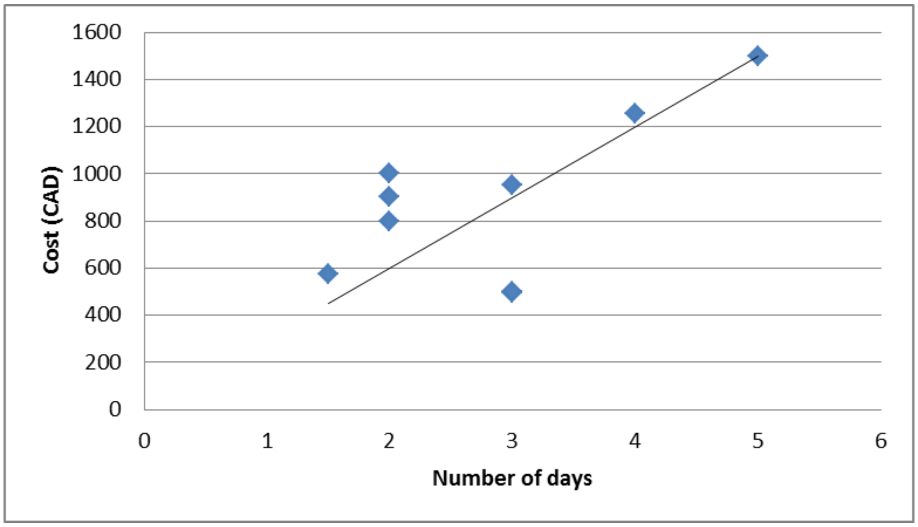

Figure 11: Duration and cost of RPAS ground school without flight training. List of service providers was retrieved from (Unmanned Systems Canada 2015).

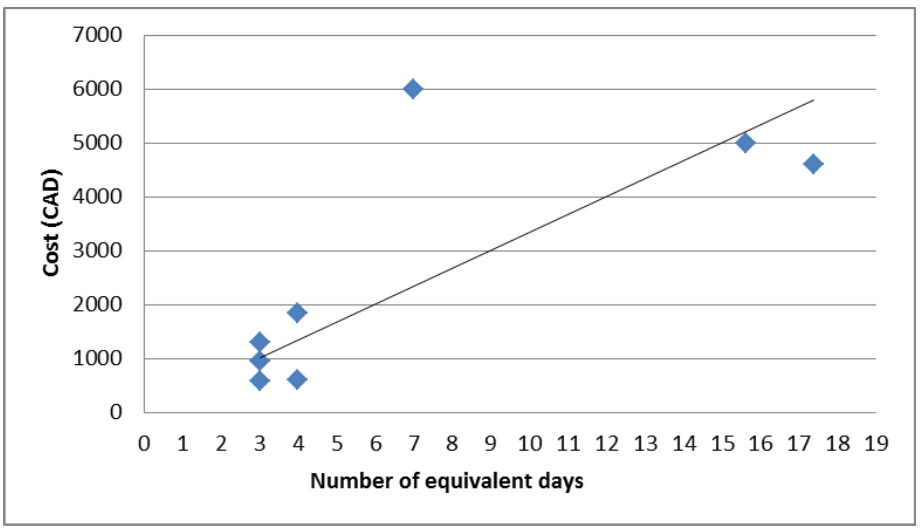

Figure 12: Duration and cost of RPAS ground school with flight training. List of service providers was retrieved from (Unmanned Systems Canada 2015). Flight- or simulator hours were converted to work-day equivalency.

5.2. Privacy Regulations

Privacy challenges raised by RPAS are directly related to their capabilities and aviation regulations. The increase in RPAS popularity is due to their reduced costs and increased flexibility relative to manned aircraft. However, their mobile nature allow RPAS to collect information from unique vantage points and in a way that makes it difficult for the public to know when and where surveys take place, and who the operators are (Office of the Privacy Commissioner of Canada 2013a). From a regulatory perspective, Transport Canada requires RPAS operations to be conducted within visual-line-of-sight due to safety concerns, yet these requirements allow for private information to be captured due to low flying altitudes. Canada's privacy laws will apply to UASs deployed by public or private sector organizations to collect and/or use personal information. RPAS operations that involve the surveillance of Canadians or the collection of personal information are subject to the same privacy law requirements as with any other data collection practice.

5.2.1. Public Sector: Federal Privacy Act and Provincial/Territorial Equivalents

The *Privacy Act* obliges federal government institutions to adhere to rules governing the collection, use, disclosure, retention, and disposal of any recorded information 'about an identifiable individual' (Privacy Commissioner of Canada, 2014). Any Canadian government department, agency, or Crown corporation seeking to implement, modify, contract out, or transfer programs involving personal information are required to complete a Privacy Impact Assessment (PIA). Because every Canadian province and territory has its own public-sector legislation these acts will apply instead of the *Privacy Act.* PIAs are a structured process that assists organizations in reviewing the impact that a new project may have on privacy, and anticipates public reactions. Likewise, federal departments will have to ensure that their RPAS programs are carried out in accordance with the Privacy Act and may need to undertake a PIA if the data from RPAS constitute the collection of personally identifiable information. As of 2014, the Office of the Privacy Commissioner of Canada has not received any PIAs regarding the use of RPAS, which indicates that federal agencies that currently use RPAS for search-and-rescue, crash-scene analysis, crime scene mapping, and environmental research do not consider the information collected to be "identifiable information" as defined by the *Privacy Act* (Privacy Commissioner of Canada, 2014).

5.2.2. Private Sector: Personal Information Protection Electronic Documents Act

The federal *Personal Information Protection Electronic Documents Act* (PIPEDA) applies when RPAS are used for commercial aims. Some provinces, including Alberta, British Columbia, and Quebec have their own private sector legislation deemed similar to PIPEDA. Private companies offering RPAS services require permission to take an individual's photograph in a public place, and the privacy protections in PIPEDA are there to ensure that people know *when* their image is being captured for commercial reasons, *what* type of footage is acquired (photograph or video), and *what* it will be used for. PIPEDA requires consent as a general rule, and the collection and use of personal information can only be for purposes that a reasonable person would consider appropriate in the circumstances. In assessing whether a reasonable person would find monitoring to be appropriate, the Office of the Privacy Commissioner (2008) developed a four part test:

- Is camera surveillance and recording demonstrably necessary to meet a specific need?
- Is camera surveillance and recording likely to be effective in meeting that need?
- Is the loss of privacy proportional to the benefit gained?
- Is there a less privacy-invasive way of achieving the same end?

5.2.3. Examples of Privacy Challenges relevant to RPAS Geomatics Applications

According to Office of the Information and Privacy Commissioner Ontario (2012), the limited Canadian jurisprudence dealing with aerial surveillance techniques cannot offer concrete guidance regarding the use of RPAS technologies and privacy. Instead, United States Supreme Court cases can provide valuable insights in the reasoning used to determine whether privacy was invaded. Privacy issues generally relate to the tort "intrusion upon seclusion", which is regularly applied in the Fourth Amendment of the United States Constitution (the protection against unreasonable searches) and recently accepted in Canadian law by the Court of Appeal for Ontario (*Jones v. Tsige*, 2012 ONCA 32). Intrusion upon seclusion is not automatically implicated for all observations of activities occurring around a home or in the public sphere, as plaintiffs must establish that the intrusion was intentional and that it would be highly offensive to a reasonable person.

Various criteria of reasonableness may be applied to determine whether intrusion upon seclusion has occurred on both public and private property (Villasenor 2013; Office of the Privacy Commissioner of Canada 2014). The court cases to-date indicate that the acquisition of still imagery with consumer-grade small- to medium-format cameras mounted on a RPAS that is flying in public navigable airspace and away from buildings would not likely violate the right to privacy (Table 20). Therefore, mapping applications to serve the needs of the surveying, natural resource, agriculture, or forest industries are unlikely to be affected by intrusion upon seclusion challenges. Neither are mapping applications within urban centers given the low frequency of image captures (e.g., once a year through an annual ortho-mosaic refresh) as long as the spatial resolution of the imagery compares with manned aerial photography missions (e.g., 2 – 10 cm; Vexcel Imaging 2008; Wiechert & Gruber 2014). The greatest likelihood of intrusion upon seclusion is through ongoing (oblique) video monitoring using RPAS, where over time the acquired video may capture peoples' activities that could lead to personal identification if the resolution is high enough, or in combination with other available information (Office of the Privacy Commissioner of Canada 2014).

Table 20: Criteria of reasonableness and relevancy to geomatics applications.

Criteria	Description	Court case reference	Geomatics relevance
General public use	Determines whether the surveillance of private property is unconstitutional if the equipment used is not generally available to the public, or whether the derived products cannot be otherwise obtained.	*Dow Chemical Co. v. United States*: an aerial inspection of an industrial facility with a sophisticated camera not generally available to the public did not need a warrant when "[a]ny person with an airplane and an aerial camera could readily duplicate" the data.	Acquisition of visible-light images using a small (consumer) RPAS with a consumer-grade camera (for the purposes of ortho-mosaics, DEM, etc.) is unlikely to be found unreasonable.
Core versus extraneous biographical detail *(Nature of the imaging technology)*	Determines whether data reveals a persons' private life, and therefore whether personal or core biographical detail is acquired. Relates to the level of detail that the camera can see instead of the level of sophistication of the camera.	*R .v. Tessling*, the Supreme Court of Canada ruled that any heat escaping from the defendant's home, which was detected by thermal cameras, was meaningless and did not reveal core biographical details.	RPAS that acquire oblique video may capture core biographical detail. An unsophisticated sensor flown at high spatial resolution can be seen as mis-use, whereas the use of a sophisticated camera at lower spatial resolutions may not raise concerns.
Public navigable airspace	Stipulates that the use of public navigable airspace is a threshold test for determining whether aerial observations are constitutional.	*California v. Ciraolo; Florida v. Riley;* manned aircraft operations need to observe minimum altitudes in order to be in public navigable airspace. *United States v. Causby:* landowners have exclusive control of the immediate reaches of the envelope.	Small RPAS operating below 300 ft. (90 m) and at a reasonable horizontal standoff from any buildings would almost always be in public navigable airspace.
Length of time	Determines whether the temporal resolution of public monitoring is reasonable.	*United States v. Jones:* extended electronic surveillance of public movements (e.g., several weeks) violated the reasonable expectations of privacy.	RPAS video monitoring or acquisition of still photography is reasonable when this is conducted infrequently (e.g., annual ortho-mosaic).

5.3. Intellectual Property Regulations

Organizations collecting, using or distributing spatial data need to understand and comply with intellectual property rights. As the data or information (e.g., video, ortho-mosaics) derived through RPAS is acquired in public navigable airspace it is not considered to be confidential information by law as someone else can acquire the same information without depriving the original owner (Hickling Arthurs Low 2011). Instead, the original data is considered property of the "author" of the work, and is protected under the *Copyright Act*. Geographic information expressed in image-based datasets is protected to the extent that the dataset may not be copied, transmitted, or disseminated either in its entirety or in substantial part, unless this is arranged in an end-user license agreement (Hickling Arthurs Low 2011). It is within the economic right of the original author to reproduce and resell all or a substantial part of the RPAS data even when this data contains sensitive information.

5.4. Trespassing and Consent

Even though RPAS will conduct missions in publically navigable airspace, Transport Canada requires RPAS operators to have permission from the owner(s) of the property on which the RPAS take-off and lands, or on which the RPAS has the potential to have strayed onto during an emergency landing (Transport Canada 2014a). Violations of the *Trespass Act* may occur when the operator does not comply with this requirement. Permission must be obtained for all property owners within 100 ft. (30 m) lateral distance of the mission boundary (Transport Canada 2014d). There is no requirement for consent from people outside of this buffer. Obtaining individual consent of all participating properties may be challenging to obtain for compliant operators tasked with data captures over larger built-up areas (e.g., municipal ortho-mosaics). In these cases a public notification (e.g., newspaper) and objection period may qualify to obtain implied consent, especially if the information is non-sensitive in nature (Office of the Privacy Commissioner of Canada 2004).

5.5. Transportation of Dangerous Goods (Lithium Polymer Batteries)

A large majority of the commercially available RPAS platforms have electric propulsion systems. These systems have batteries based on lithium polymer (LiPo) chemistry that offer a high-energy storage to weight ratio. Although LiPo batteries are the main battery of choice for small RPAS systems, special care in terms of battery storage and charging is required due the high energy density. Any lithium battery is considered a dangerous good, and falls under under the International Air Transport Association (IATA) Dangerous Goods Regulations, and by extension Canada's Transportation of Dangerous Goods Act (1992) and its' Regulations.

There have been several incidents of lithium batteries overheating and catching fire (e.g., electric hover-boards). In response to the incidents, the International Civil Aviation Organization (ICAO) has banned large LiPo batteries as cargo on passenger aircraft and has placed restrictions on smaller LiPo batteries (IATA 2016). These bans and restrictions affect the transportation of lithium batteries for RPAS projects that require air travel. Whether a battery can be carried by air depends on its Watt-hour (Wh) rating. IATA regulations ban LiPo batteries over 160 Wh from passenger aircraft or passenger-cargo combi-aircraft. To ship these batteries they must be sent on a cargo-only aircraft and packed in accordance with IATA Dangerous Goods Regulations. Alternative solutions based on dual batteries of a reduced Wh-rating connected in parallel can be used if cargo-only services do not exist or are too costly. For LiPo batteries ranging between 100 Wh and 160 Wh there is a maximum of two units that can be taken as carry-on baggage only. Batteries rated less than or equal to 100 Wh can be taken as carry-on only, but no limit applies.

6. RPAS BEST PRACTICES IN GEOMATICS

6.1. Best Practices in Project and Program Design

6.1.1. Stakeholder Communication

Understanding subject matter expert information gaps and the ability of RPAS to support that information gap is required in order to define the roles in which RPAS can become operational. Despite their increased exposure to photogrammetry and remote sensing, subject matter experts often must rely heavily on technical specialists to design and implement services based on remotely sensed data. Lessons from satellite remote sensing indicate that due to differing technical backgrounds and professional languages, cross-sectorial communication between subject matter experts (e.g., natural resource managers, ecologists) and remote sensing professionals is often challenging (Arnold et al. 2000; Kuenzer et al. 2014). Information gaps are generally not directly defined in terms that can be converted to remote sensing language, and there is a wide spectrum of unmanned aircraft, sensors, and methodologies that could be applied to a particular challenge. An iterative discussion between the technical experts and the application domain experts is critical for both parties to be able to define an operational program or service with a reasonable chance of success, yet this discussion is often the most challenging (Pettorelli et al. 2014). For example, decision makers typically want to know what remote sensing or RPAS can do for their operations while photogrammetry or remote sensing experts typically want to know the end-users' specific information needs. End users may not have an understanding of remote sensing while remote sensing experts may not have an understanding of the relevant characteristics of the indicators that need to be measured.

At its core, geomatics provides a means of understanding, analyzing, and communicating results concerning information gaps. Geomatics technology is therefore being used to serve as a means to an end, and not an end on its own. Hence the initiation and continuation of dialogue between disciplines (e.g., RPAS specialists, remote sensing specialists, end users, decision makers) creates an improved understanding of each discipline's assets and challenges. RPAS program managers or those seeking to integrate RPAS in their programs or services should establish a central role in these discussions where the end-user challenges and the techniques that may overcome these problems are known. The development of collaborative projects provides an avenue to develop specific solutions to the problems identified by end-users or decision makers, after which an operational program or service can be established. Strong communication channels are needed to develop a coordinated approach that will establish an achievable goal and a clear view on why and how RPAS can help in that goal. RPAS can improve situational awareness and acquire site-specific information, yet to make this accessible and interpretable requires the integration within existing enterprise asset management systems (EAM), enterprise resource planning systems (ERP), or geographic information systems. To be successful, a decision support system should be designed to help a well-defined target group make better decisions within the context of their typical operations (Arnold et al. 2000).

6.1.2. Privacy and Sensitive Information Management

Issues pertaining to the use of RPAS technology can be mitigated by ensuring that applications are justified, necessary, and proportional to the objectives of a program or service, and are prescribed in a transparent accountability structure whereby privacy and public awareness are of main importance. When RPAS missions are conducted in built-up areas the missions should ideally be conducted with sensor technology that is in general public use, in public navigable airspace, and should acquire aerial footage at a spatial and temporal scale at which no personal identifiable information can be obtained (e.g., > 5 cm spatial resolution).

As issues related to privacy will be at the forefront of the implementation of UAS technology into government programs, the Privacy Commissioner of Ontario (2012) recommended a proactive response by addressing these issues through a "Privacy by Design" framework (Table 21). This framework is useful for policy development in which agencies can leverage the benefits of RPAS technologies while protecting expectations of privacy. These best practices include public notifications of RPAS missions, purpose specification, a designation of a point-of-contact who is accessible to the public, and the development of appropriate data handling procedures.

Table 21: Privacy by Design framework.

Pillars	Description
Proactive not Reactive; **Preventative** not Remedial.	Anticipation and prevention of privacy-invasive events. Formulate usage restrictions.
Privacy as the **Default Setting**	Ensure that personal data are automatically protected in any IT system, where no action is required by the individual.
Privacy **Embedded** into Design	Practices are put in place to safely eliminate unnecessary data that has a strong possibility of having personal information
Full Functionality – **Positive-Sum**	Avoiding the presence of false dichotomies and ensure to accommodate all legitimate interests of relevant stakeholders
End-to-End Security – **Full Lifecycle Protection**	Conduct privacy impact assessments (PIA) in situations where personal identifiable information may be collected
Visibility and **Transparency**	Consultations with relevant stakeholders and full public disclosure of RPAS usage (e.g., annual reports)
Respect for User Privacy – Keep it **User-Centric**	Public notifications of RPAS missions and establishing a technology-neutral process for communication

Source: Privacy Commissioner of Ontario (2012).

The data collected by RPAS are managed within the overall ICT infrastructure of an organization and are subject to internal data management standards with respect to sensitive information and national, provincial, or territorial privacy laws. Beyond privacy, sensitive information can include thematic geospatial data for purposes such as environmental impact assessments, land use planning, and resource management (Amec Earth and Environmental 2010). Implementing clear RPAS-specific privacy and sensitive information policies can be challenging due to the breath of RPAS users and uses (Riopel et al. 2014) and because there are no consistent mechanisms to assess sensitivity as this concept changes with context and policies (Amec Earth and Environmental 2010). Nevertheless, best practices and guidelines can be formulated that can help identify and mitigate risks arising from the collection, use, retention, disclosure and disposition of personally identifiable or otherwise sensitive geospatial information.

Standardized guidelines and categories of information are required to implement effective privacy and sensitive information management approaches. These mechanisms will assist data custodians in understanding which aspects may apply to the dataset that will be collected, used, or disclosed (Table 22). Although each organization has to establish and document their own criteria to conduct these reviews across the breadth of datasets that it manages, collaborations across jurisdictional boundaries will prevent contradictory decisions of the same information (Amec Earth and Environmental 2010). It is also imperative to develop these criteria independent of any specific dataset, establish them in advance of any assessment, and have the protocol vetted by an authorized organizational representative (e.g., legal or policy) to establish a baseline against future challenges (Amec Earth and Environmental 2010). As such, the data that RPAS can acquire will fall under a range of existing sensitivity classes, and the integration of RPAS into operational programs should lead organizations to review dataset categories and associated sensitivity criteria to ensure these are up-to-date and relevant.

Table 22: Aspects of Geospatial Information Privacy Protection.

Factor	Description
Characterization	The characterization of data as personal (or identifiable) information or non-personal (or non-identifiable) information is key to its proper treatment in privacy law
Context	The context within which information occurs has a direct and important impact upon its interface with privacy law and policy (e.g., highly sensitive dataset, small geographic/demographic size)
Consultation	Given the uncertainties when characterizing geospatial information, it is best to consult with appropriate resources when doubt exists
Consistency	Each organization should make a concerted effort to ensure that it adopts a consistent approach to deal with potentially identifiable geospatial information (e.g., centralized records of how data elements are characterized and treated)
Cumulative	Geospatial data elements that are not identifiable when considered individually may become identifiable when combined with other data elements, which will depend on the circumstances of each case.
Caution	Precautionary approach that limits actions when no informative decision can be made regarding the collection, use, or release of elements of geospatial data
Constraint	Dissemination of personal or non-personal information to third parties is best conducted by restricting the data recipient’s rights via a contract and use of metadata.

* Source: Canada Privacy Services Inc. (2010).

6.1.3. RPAS Program Development

The development of a RPAS program or commercial service requires considerable resources, senior management support, regulatory compliance, and time. Program development requires a step-wise, incremental approach to build organizational capacity, and to bridge the gap between organizations who have started the integration of RPAS in their organization and those who intend to do so, an overview of program development steps are provided for reference (Table 23).

Table 23: Phases of RPAS program development.

Phase	Purposes	Description
Technical Investigation	To scan internal & external environment To demonstrate RPAS utility	• Conduct a situational analysis of issues and potential solution scenarios that can be address by high resolution imagery and video • Review the utility of different RPAS platform and sensor characteristics • Review regulatory requirements to meet solution scenarios • Review costs to meet solution scenarios • Establish a list of ideal characteristics to meet solution scenarios • Purchase a low-cost option to demonstrate range of solution scenarios (or purchase contractor services) • Develop Draft standard operating procedures (SOP) and manuals • Obtain regulatory approval for missions (e.g., SFOC) • Develop a Draft Policy to guide organizational use based on experience gained (key elements: flexibility towards regulatory environment)
Approval of Phase Expansion	To gain management support	• Present and demonstrate solution products to Senior Management Staff • Provide basic costing through supported training and access to pooled RPAS resources that can be shared among units • Obtain Senior Management support to proceed with next Phase
Field Deployment Feasibility	To continue momentum To obtain participant input To establish capacity	• Seek commitment across units to provide initial recruitment of RPAS pilots (mix of highly motivated and critical personnel) • Acquire central funding to purchase complete RPAS kits for recruits • Refine Draft Policy to guide RPAS use and share Policy with recruits • Use Draft Policy to manage expectations and limit use beyond recruits • Refine Draft SOP and manuals • Develop tracking system with information about pilots, flights, equipment • Conduct ground- and flight-schools (where possible partner with industry) • Obtain regulatory approval with additional recruits (e.g., standing SFOC) • Provide shared network solution for documentation and updates • Conduct missions and keep open flow of two-way communication • Conduct workshop to share experiences and propose changes to program • Acquire metrics (flight hours, data volume, cases) of flight-season • Conduct Phase evaluation using metrics, identify challenges/solutions
Program Execution	To define & implement Program To maintain management support	• Define Program goals, timelines, and human/financial capacity assessment • Renew SFOC • Procure additional RPAS kits • Define program champions who acquire expertise in program elements • Further refine Draft Policy, SOP, manuals, tracking system, training • Expand partnerships with industry, academia for R&D • Monitor indicators of success and establish management frameworks • Continued experience sharing via workshops

Source: Ministry of Environment, Government of Saskatchewan. This Ministry has a RPAS programme which is the first of its kind in Canada, is in its third year, and has trained 50 RPAS pilots (May 2016).

6.2. Best Practices in Mission Planning

Before mission planning is conducted an organization should verify whether a SFOC is required (Section 5.1). Mission preparation is an essential step for geo-referenced data acquisition. RPAS are small aircraft that are sensitive to wind and wind gusts, and can therefore be bounced from their planned flight-path. This could result in missed way-points or off-nadir photos. Missing or off-nadir photos can reduce photo-overlap and affect the coverage or accuracy of the final mapping deliverables due to a weaker geometry of the photogrammetric 3D network. To compensate for aircraft instability RPAS photogrammetric acquisitions are typically planned with a high overlap (> 75%) and side-lap (> 60%) to strengthen 3D geometries (Colomina & Molina 2014; Whitehead et al. 2014). Complex structural (e.g., forests, mountainous) or feature-less terrains (e.g., snow, sand) often have a different appearance between overlapping images, and require even higher overlap and side-lap (85% - 90%) as well as a higher radiometric resolution sensor (i.e., sensor sensitivity to reflected energy). Mission planning for corridors (e.g., railways, roads) generally requires at least two flight-lines at 85% overlap and 60% side-lap. To acquire ortho-mosaics and 3D data of built-up areas a double grid acquisition plan is often used to capture the facades of buildings from all directions (Figure 13). The accuracy of RPAS point-clouds is typically 1 to 2 times the spatial resolution in horizontal coordinates and between 1.5 and 3 times the spatial resolution in vertical coordinates (Section 3.3). Hence accuracy tolerances must be established that meet the mapping objectives, after which the required camera equipment, accuracy of the ground control points, and the altitude of the RPAS can be determined. This planning sequence avoids "over-engineering" where the mapping products are much more robust than what is necessary for the application.

Beyond the complexity of the surface to be mapped, flight plans should accommodate the wind conditions of the mission area at the time of mission execution. A high wind speed may cause a fixed-wing RPAS to fly too fast to capture overlapping images as specified. To reduce the chance of data gaps the direction of flight-lines are often chosen to be perpendicular to the prevailing winds (Cryderman et al. 2014). Although perpendicular flight-lines will result in the crabbing of the aircraft, the consistent airspeed will benefit the image acquisition. The variability in wind conditions highlight why mission planning should ideally be conducted in the field to capture the real-time conditions of the site.

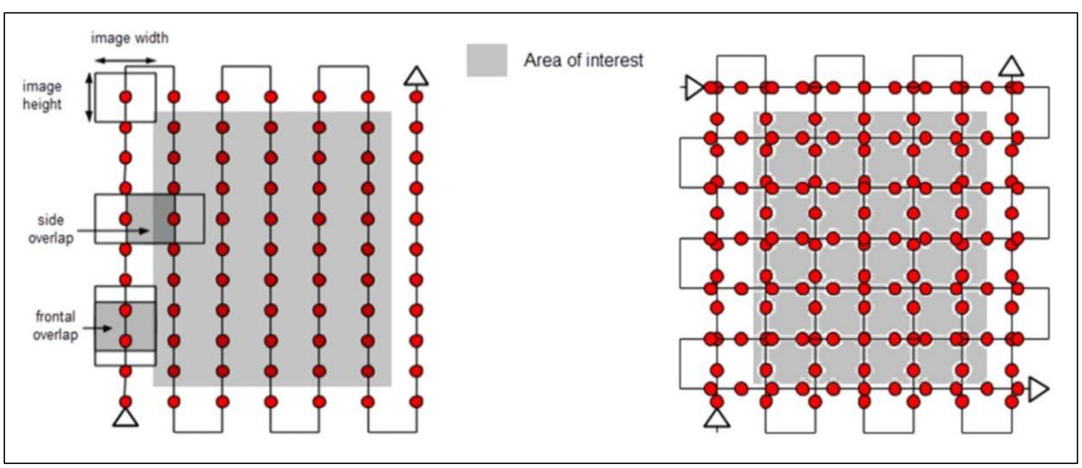

Figure 13: Ortho-mosaic flight plans: general case (left) and for an urban area (right). After Pix4D (2015b).

6.3. Best Practices in Field Operations

6.3.1. Site Survey, Communication, Weather, and Consent

To safely conduct a RPAS mission an assessment of the suitability of the operating location should be conducted (Table 24). Multiple data sources can be used, including site visits, aeronautical charts (e.g., Visual Flight Rules; VFR Navigation Charts from Nav Canada, Canada Flight Supplement, *Foreflight.com*, *Fltplan.com*), and web-mapping tools (e.g., *Google Maps*).

Table 24: Elements of a RPAS site survey (Transport Canada 2014d).

Mission Limitations	Hazards
• Defining and visualizing the boundaries of the mission area • Class of airspace and specific provisions • Altitudes and routes on the take-off and landing • Limitations and/or restrictions of local by-laws • Predominant weather conditions for the site • Minimum distances from persons, structures	• Proximity of aerodromes including heliports and seaplane bases • Hazards associated with nearby industrial sites • Areas of radio transmissions or interference • Location and height of obstacles (e.g. wires) • Security provisions to limit public access • Built-up areas, major roadways

Airspace coordination and communication are paramount to ensure flight safety. To ensure RPAS operators are familiar with air traffic services coordination, NAV Canada has produced best practices for operations for the Edmonton and Vancouver Flight Information Regions (NAV Canada 2015a; NAV Canada 2015b). These best practices include the appropriate sequence of and timing communication with NAV Canada and Air Traffic Control, requirements for NOTAM's, emergency contact procedures, and points of contact.

Temperature and wind conditions should be monitored as lower temperatures (≤ 0°C) and stronger winds limit the available battery power and therefore flight-time of the RPAS (Puliti et al. 2015). As RPAS and consumer cameras are usually not specifically designed to operate in freezing conditions, relatively common Canadian winter temperatures of -10°C can freeze RPAS and camera batteries. Missions during wind speeds beyond 40 km/h are generally not advised due to safety or data quality concerns (Laliberte et al. 2010; Rosnell et al. 2011; Siebert & Teizer 2014). Missions must be conducted within the operating limitations of the aircraft, and icing conditions must be monitored.

Although there is no requirement for legal consent or permission for non-participating persons or properties outside of the 100 ft. (30 m) buffer of the mission area, the use of public signage, door-to-door notification, and community consultations can be used to let the surrounding environment know of the RPAS operation. This is an effective, proactive approach for missions in built-up areas, and provides non-participating persons the opportunity to know *when* the mission will occur, *what* type of footage is acquired, *what* it will be used for, and *who* is conducting the mission.

6.3.2. Data Acquisition

According to Transport Canada regulations, RPAS missions must take place at least one hour after sunrise and one hour before sunset. Ideal weather conditions feature consistent illumination (e.g., full overcast with a high cloud ceiling; Hird & Mcdermid 2016). Image acquisitions are best performed near solar noon to minimize shadows, and repeated missions should be conducted at the same time of day to minimize illumination effects (Laliberte et al. 2010; Rosnell et al. 2011).

The amount of light reaching a sensor is typically controlled by the exposure time and f-stop (aperture), and the signal amplification is controlled by the ISO setting. There are two approaches to ensure the acquisition of high quality and consistent imagery. One approach is based on acquiring imagery with an auto-exposure setting and correcting the imagery to one common exposure level during the data processing stage (Ritchie et al. 2008). This approach typically increases the dynamic range and reduces the risk of over- and under-exposure of individual images at the expense of more complicated data processing. Another approach seeks manual parameters that minimize changes in the radiometric properties of the image at the time of data collection, yet with possible signal-to-noise and image saturation consequences. In the latter case manual shutter speeds of 1/1,200 to 1/3,200 can minimize image blurring as a result of platform vibrations and on-flight movements (Rosnell & Honkavaara 2012; Lucieer, de Jong et al. 2014). A motion blur of less than half of the spatial resolution of the ortho-mosaic is desirable (e.g., 1 cm spatial resolution / 2 / 5 m/sec groundspeed = 0.001 sec; 1/1000 shutter speed). High quality imagery is typically acquired with mid-range f-stop settings between f/3.5 and f/5.6, and with ISO sensitivity settings between 100-200 and 200-400 for point-shoot and DSLR cameras, respectively (Rosnell et al. 2011; Cryderman et al. 2014). Although smaller f-stop values (i.e., large apertures) let in more light per unit of time than mid-range apertures (i.e., smaller apertures), mid-range apertures yield sharper photos at the corner of images and reduced levels of chromatic aberration (Wolstenholme 2013). A manual focus length should be set to allow for faster image acquisition, and should be set at slightly less than infinity yet beyond the hyperfocal distance to reduce the chance of blurry images (the infinite setting is often not calibrated on consumer cameras). The camera should ideally be placed on a gimbal capable of slight tilts away from nadir to minimize the effect of doming artifacts in the 3D models as a result of incorrect radial camera calibrations (James & Robson 2014).

The horizontal and vertical accuracy of ortho-mosaics and 3D terrain models is greatly improved by ground control points (GCP) (Clapuyt et al. 2015; Harwin et al. 2015). GCPs should be equally distributed across the survey area and the density should be sufficient enough that it will describe the topographic complexity. GCPs are typically made up of material that is easy to transport (e.g., 0.5m x 0.5m coloured sheets, 5 gallon plastic pales, bright orange aluminum disks). Temporal analysis of landform change (e.g., aggregate removal of stockpiles) requires highly accurate GCP measurements to minimize error propagation, and in such cases a dual-frequency (L1/L2) GNSS or total station is required. The acquisition of GCPs requires significant effort on the ground, however, RPAS software packages such as *Pix4D* or *Agisoft* require a minimum of 3 GCPs for improved 3D reconstruction and achieve diminishing improvements in accuracy beyond 10-15 GCPs. In addition to GCPs, a minimum of 25 check points are required to independently measure the accuracy (mean, RMSE, 95% confidence interval) in case the deliverables must adhere to standards (ASPRS 2015a).

In terms of video acquisitions, recent improvements in the availability of 4K video sensors may provide a clearer picture due to the quadrupling of the number of pixels. However, video acquired at 1080p resolution is likely to be sufficient for site documentation and asset management due to the relatively low flying altitude of RPAS and because the data volume may exceed network capacity and storage. For example, a compressed 4k video with standard frame rates (24-30/s) has a bit rate of 30-50 Mbps (megabit per second), which is much higher than the 8 Mbps bit rate for standard 1080p videos (8 Mbps = 1 MBps; Megabyte per second). Instead of increasing video resolution, greater (value-added) functionality can be acquired from the data by embedding GNSS and IMU telemetry information in the video frames through the Motion Imagery Standards Board (MISB) protocol. This metadata georeferences the video frames for use and archive within a GIS (e.g., *ESRI ArcGIS Full Motion Video Add-in, Hexagon Geospatial Motion Video Analyst Professional, ENVI Full Motion Video Player, Remote Geosystems LineVision*).

6.4. Best Practices in Data Processing

Knowledge of best practices related to RPAS data processing is comparatively sparse due to the relatively early market for operational RPAS platforms, sensors, and software packages. The conversion of raw RGB and NIR images to ortho-mosaics and digital surface models requires little user input in highly automated software packages such as *Pix4D Mapper* and *Agisoft Photoscan*, or cloud-based services such as *DroneDeploy*. The limited parameterization of these applications prevent the identification of best practices, however some best practices can be formulated with respect to the resolution of the final end-products, the acquisition of bare-earth digital terrain models and canopy height models, accuracy assessments, and quantitative spectral analysis.

The spatial resolution by which raw RPAS imagery is acquired ranges from a few millimeters (e.g., 0.006 m; Mancini et al. 2013) to a few centimeters. Producing ortho-mosaics and digital terrain information at these spatial resolutions typically exceed user needs and/or computing capacity, and therefore the final end-products are resampled to a more usable spatial resolution. RPAS imagery can be used to derive 3D point-cloud densities of hundreds to thousands of points/m^2, which renders the definition of break-lines largely unnecessary (Cryderman et al. 2014) and reduces the effects of interpolation type and parameters on the final accuracy of the gridded terrain model (Wiseman & van der Sluijs 2015). In digital photogrammetry the highest attainable terrain model resolution is typically five times greater than the spatial resolution of the images acquired by the sensor (Westaway et al. 2003). Such resampling overcomes the inherent accuracy and precision limitations of the 3D point-cloud (e.g., vertical accuracy is 1.5 – 3 times the spatial resolution of the dataset). For RPAS-specific applications, studies generally obtain mapping products at 5-13 times the spatial resolution of the raw images (e.g., 0.1 to 1.0 m final products; Niethammer et al. 2010; Mancini et al. 2013; Lucieer, de Jong et al. 2014; Wiseman & van der Sluijs 2015).

Software packages based on structure-from-motion processing converts raw images into ortho-mosaics and Digital Surface Models (DSM), whereby the gridded values represent the elevation of all surficial features including vegetation and buildings. DSMs contain vegetative features that are undesirable for topographic surveying, and as such DSMs are typically post-processed to derive the elevation surfaces of the bare surface (i.e., digital terrain model – DTM). DTMs can be produced through the interpolation of a sparse point-cloud due to the reduced sensitivity to the effects of vegetation (Hugenholtz et al. 2013). Furthermore, DTMs can be generated through a point-cloud classification procedure to separate ground-points from non-ground points, and subsequently the interpolation of the ground-points (Jensen & Mathews 2016). If successful, both of these techniques can be used to generate Canopy Height Models by subtracting the elevation values of the ground points from the elevation value of the non-ground points (Figure 14). However, careful processing is required to generate Canopy Height Models as point-cloud thinning parameters and storage of elevation data (e.g., rasterized DTM, DSM versus Triangulated Irregular Network; TIN) can affect their quality (Khosravipour et al. 2014). Unlike LiDAR, RPAS point-clouds may be not be suitable for topographic reconstructions of densely vegetated areas when the imagery cannot penetrate the vegetative canopy. In these situations a separate high resolution DTM can be used to calculate canopy heights (e.g., LiDAR; Figure 15).

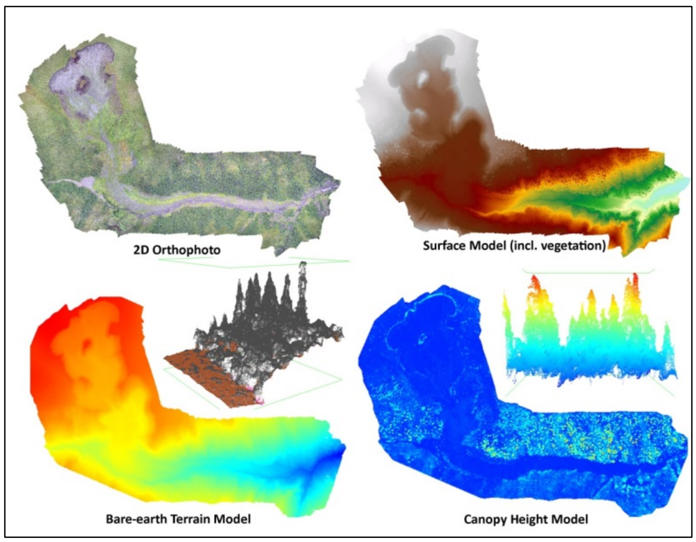

Figure 14: Overview of RPAS derived terrain model types from a permafrost thaw slump study site in the Northwest Territories, including digital surface model, a filtered bare-earth terrain model, and a canopy height model. Data used from Fraser et al. (2015).

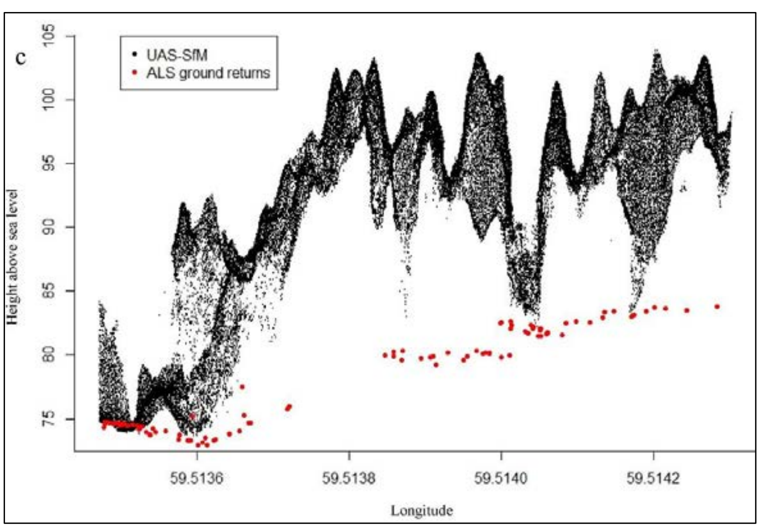

Figure 15: Calculation of canopy height by subtracting airborne LiDAR (ALS) measurements from RPAS point-clouds (Puliti et al. 2015).

Digital geospatial data such as DTMs require an accuracy assessment based on accepted guidelines by industry associations (e.g., American Society for Photogrammetry and Remote Sensing; ASPRS) to determine whether the data meets a certain standard (ASPRS 2015a). DTMs derived through RPAS are no different, especially for applications dependent on highly accurate 3D measurements. At present, the majority of RPAS studies compute vertical accuracy (RMSE) based on a finite set of check points from which the differences (residuals) are calculated between DTM heights and height values from an independent source of higher accuracy (Hugenholtz et al. 2013; Mancini et al. 2013; Cryderman et al. 2014). The ASPRS (2015a) guidelines recommend that for open terrain the vertical accuracy must be reported at the 95% confidence level (i.e., 1.96 x $RMSE_z$), and that for vegetated areas the 95% percentile of the absolute value of the vertical errors is provided. These measures indicate that 95% of the errors in the data-set will have absolute values of equal or lesser value and 5% of the errors will be of larger value (Aguilar et al. 2007). In comparison to RMSE, these measures provide the user of a RPAS-derived DTM with a better description of how well each cell represents the true elevation (Wiseman & van der Sluijs 2015). When computing the 95% confidence level estimates, it is assumed that errors are normally distributed, that significant systematic errors (i.e., mean errors) have been removed, and that the data provider tests for kurtosis or skewed error distributions prior to data delivery. ASPRS (2015a) recommends a minimum of 25 check points for projects smaller than 500 km^2, which should be distributed proportionally among the various vegetative and non-vegetative land-cover types.

DTMs are often differenced (e.g., DTM_{T2} – DTM_{T1}) to accurately quantify temporal changes in topography for applications such as landslide monitoring (Niethammer et al. 2010; Lucieer, de Jong et al. 2014) and earthwork volume calculations (Cryderman et al. 2014; Siebert & Teizer 2014). DTM differencing increases uncertainty in the volumetric change detection as the errors of the individual DTMs are multiplicative. As such it cannot be assumed that the accuracy associated with an individual DTM is the precision associated with the differences between two DTMs (Westaway et al. 2003). To overcome this uncertainty, point-clouds can be co-registered using stable features. If this is not possible, Hugenholtz et al. (2013) proposed the use of Equation 1 to determine the threshold value (±T), meaning that any elevation differences exceeding the range of this threshold are more likely to represent actual topographic changes..

$$T = \pm 3 \text{ x} \sqrt{(RMSE_{DTM1})^2 + (RMSE_{DTM2})^2} \qquad (1)$$

Three-dimensional point-clouds created through RPAS-specific photogrammetric packages are commonly stored as X, Y, and Z coordinates in LiDAR format (.LAS) due to convenient file handling (compared to ASCII) and its non-proprietary nature (compatibility between vendors). Furthermore, the point-cloud captures the environment in truly 3D fashion (i.e., an X and Y coordinate can have multiple Z values), unlike raster- and TIN-based representations which can only store one possible Z value for every X/Y coordinate (i.e., 2.5D). The ASPRS LAS format is a reliable and consistent form to store and exchange LiDAR and other 3D data, and has evolved as the industry standard (Boehm & Liu 2015). A total of 20 bytes are required to store a single 3D point in LAS format, which can result in Big Data challenges when considering that RPAS derived point-clouds often consists of hundreds to thousands of points/m^2.

Currently, RPAS point-clouds derived through SfM packages are spatially incoherently stored, contain noise, and may have excessive spatial precision (millimeters instead of centimeters). The highly detailed data products result in large file-sizes if left unmanaged, and with a long-term focus on operational sustainability, efficient and standardized analytics and data storage methods should be used. The most common approach to improve LAS data processing speed and reduce data volume is a lossless compression to LAZ format, whereby file sizes are typically reduced to 7-25% of the original LAS file with no loss of information (Isenburg 2013; Deems et al. 2013; McKittrick 2015). The LAZ format utilizes the open-source LASzip library and although it is not an ASPRS-sanctioned format, it is based on the ASPRS LAS specification with respect to point classes and attributes. The compressed LAZ files behave similarly to standard LAS files, whereby they can be readily used during data processing (e.g., point-cloud classification) without the need for decompression. Beyond the mere compression of LAS files to LAZ format, further best practices include the rescaling of point values from millimeter precision to centimeter precision, the spatial indexing to speed up access to relevant areas of the dataset during spatial queries, the re-ordering of points according to their X/Y position in a 2D Morton space filling curve, and the tiling of large LAZ files to allow for multi-core processing (Harwin & Lucieer 2012; van Oosterom et al. 2015).

Beyond 3D reconstructions, image quality and illumination problems inherent in RPAS imagery have resulted in challenging data processing pipelines to use the ortho-mosaics for quantitative spectral analysis (e.g., image classification) (Colomina & Molina 2014; Whitehead & Hugenholtz 2014). Users deploying multi-spectral and hyper-spectral sensors are challenged by issues related to sensor calibration, atmospheric correction, and band-to-band image registration which have resulted in sensor- and application-specific image processing chains (Laliberte et al. 2011; Zhang & Kovacs 2012; Proctor & He 2015). As such the acquisition of calibrated reflectance data and vegetation indices is currently outside of the realm of the general RPAS data user due to a lack of user-friendly software to produce this data (Candiago et al. 2015). Nevertheless, this continues to be an active area of research where many studies have published experimental image processing pipelines (Laliberte et al. 2011; Honkavaara et al. 2013; Lucieer, Malenovský et al. 2014; Näsi et al. 2015), and thus it is only a matter of time before consensus has reached regarding best practices. Once the spectral data is properly calibrated, object-based image analysis has been shown to be more suitable than pixel-based image classification algorithms as it can take advantage of shape, textural, and contextual attributes to retrieve the desired thematic information of the RPAS imagery (Laliberte et al. 2010; Whitehead et al. 2014; Chrétien et al. 2015).

7. RISK MANAGEMENT RELATED TO RPAS OPERATIONAL PROGRAMS

This section synthesizes RPAS capabilities, the status of regulations, and best practices with the aim of identifying risks and management strategies.

7.1. Aviation Regulations

RPAS can provide a wide range of operational geomatics applications for small to regional scale work in areas that are currently difficult to access, labour-intensive, and/or expensive to monitor. For many RPAS the maximum visual-line-of-sight is about 800 m, which usually yields a maximum possible coverage of 64 ha if the operator and visual observer is located at the edges of the area of interest (800 m x 800 m), or 256 ha if positioned at the centre of the area of interest (1.6 km x 1.6 km). With 3 to 4 flights a day depending on RPAS characteristics, data requirements, logistics, and amount of daylight (Whitehead et al. 2014; Puliti et al. 2015), a maximum daily coverage between 750 – 1,000 ha (7.5 km^2 – 10 km^2) can be achieved under ideal circumstances. This coverage generally meets the needs of end-users seeking time- and GNSS-stamped aerial photographs and video for up-to-date site documentation, situational awareness, and local mapping data. However, from a risk perspective one of the most frequently reported challenges is the length of the SFOC application process, where Canadian organizations identify permission to fly and the inability to quickly respond to customer needs as major challenges (Baillie et al. 2014). The Notice of Proposed Amendments (Transport Canada 2015b) highlighted that organizations will be able to fly missions in urban settings (low threshold RPAS or small RPAS complex) and rural settings (small RPAS limited) without SFOCs. These changes allow organizations to obtain information in a short turn-around for time-sensitive decision making. The amendments will reduce short-term organizational risk by decreasing the uncertainty regarding the timeframe of missions, and will lessen long-term organization risk as further regulatory changes regarding sub-25 kg RPAS missions conducted within visual line-of-sight are unlikely. However, implementation delays create uncertainty that is difficult to mitigate unless Transport Canada compliant systems are used in the meantime.

The altitude restriction of RPAS missions is another key constraint (Baillie et al. 2014; Whitehead & Hugenholtz 2014). With a maximum operating altitude of 300 ft. (90 m) and 400 ft. (120 m) for simplified and complex missions, respectively (Transport Canada 2014d), RPAS mapping surveys are restricted to low-altitude missions that can acquire very high spatial resolution imagery (e.g., 1 – 3 cm) depending on the sensor specifications. Although these altitudes may meet the needs for end-users requesting oblique aerial photographs and video, imagery at these spatial resolutions may exceed user mapping needs or hardware capacity as many additional images are required to cover the surveyed area. For example, increasing the maximum altitude from 300 ft. (90 m) (i.e., small RPAS limited operations) to 500 ft. (150 m) (Federal Aviation Administration 2015) reduces data volume by a factor of 3 to cover a 24 ha quarry (Figure 16). Beyond the data management challenges this affects data processing pipelines due to the effects of relief displacement and tree lean that challenges ortho-mosaic production (Figure 17; Whitehead & Hugenholtz 2014; Puliti et al. 2015). To improve operational efficiency the maximum altitudes of small RPAS would ideally be increased, yet organizations will need to obtain SFOC approval to fly at higher altitudes or seek solutions to overcome data processing and management challenges (Section 7.3, 7.5).

Figure 16: Mission plans for a 24 ha quarry survey at 90 m (left) and 150 m (right) altitude with photo centers. Note: calculated for a RPAS with a Canon S120 camera, 80% overlap, 70% side-lap. 310 and 110 photos, respectively.

Figure 17: Example of high relief displacement with trees leaning away from the center of the image. Data from Fraser et al. (2015).

7.2. Privacy

Issues related to privacy violations will be at the forefront of the implementation of RPAS technology into government and commercial programs, particularly within the geomatics sector. Despite a plethora of negative press coverage related to military drones, many RPAS applications are welcomed, and are approved by, the Canadian public (Office of the Privacy Commissioner of Canada 2013b; Office of the Privacy Commissioner of Canada 2014). Canadians are generally comfortable with RPAS being used for search-and-rescue, border patrol, law enforcement investigations, and the oversight, maintenance, and management of industrial property (e.g., pipelines). However, the prospect that RPAS are used for public surveillance and/or individual identification during public events or demonstrations is controversial due to potential privacy violations. Public awareness around RPAS applications is often minimal, and the general public is seeking more information with respect to the reasons of RPAS use and the institutional affiliations (Office of the Privacy Commissioner of Canada 2014). Unfortunately, the administration of RPAS regulation among various regional Transport Canada offices have contributed to a partial knowledge bank on the details of specific RPAS flights (e.g., location, purpose), which challenges informed decision making regarding legislation and policy development (Thompson & Saulnier 2015). In the absence of accessible and transparent accountability structures and purpose specifications, the geomatics sector could be negatively affected if policies are implemented that:

- Do not reflect accurate statistics on RPAS use in geomatics,
- Exclude important sub-sectors that the geomatics sector currently serves (e.g., urban),
- Discourage research and development of sensors and applications covered by new policies.

What follows is that the RPAS operators in the geomatics sphere have much to gain about a straight-forward reporting system which specifies the commercial or government organizations that operate RPAS and for which purposes. Advocated by the Office of the Privacy Commissioner of Canada (2014) and acknowledged by Transport Canada (2015b), such a system can provide data to improve the public's awareness and acceptance of RPAS video and mapping applications through outreach and education, as well as public consultations. For example, the data will help support case studies produced by commercial and government organizations highlighting how RPAS can alleviate dull, dirty, and dangerous work in both remote and urban settings. A transparent approach with checks and balances will likely lead to the lowest risk impacts for all stakeholders.

7.3. Data Quality of Modified Near-infrared Sensors

There are several important considerations that RPAS operators and data users should make when selecting modified near-infrared sensors or using the data derived through these sensors. First, with the removal of the near-infrared filter the other channels become sensitive to near-infrared light as well, thereby contaminating other bands by including light measurements from wavelengths not in the region of interest (i.e., cross-talk; Figure 18) (Hunt et al. 2011). This can result in unreliable Digital Number outputs and reduced seperability between bands (Nijland et al. 2014). This makes the data less useful for modeling and image classification purposes.

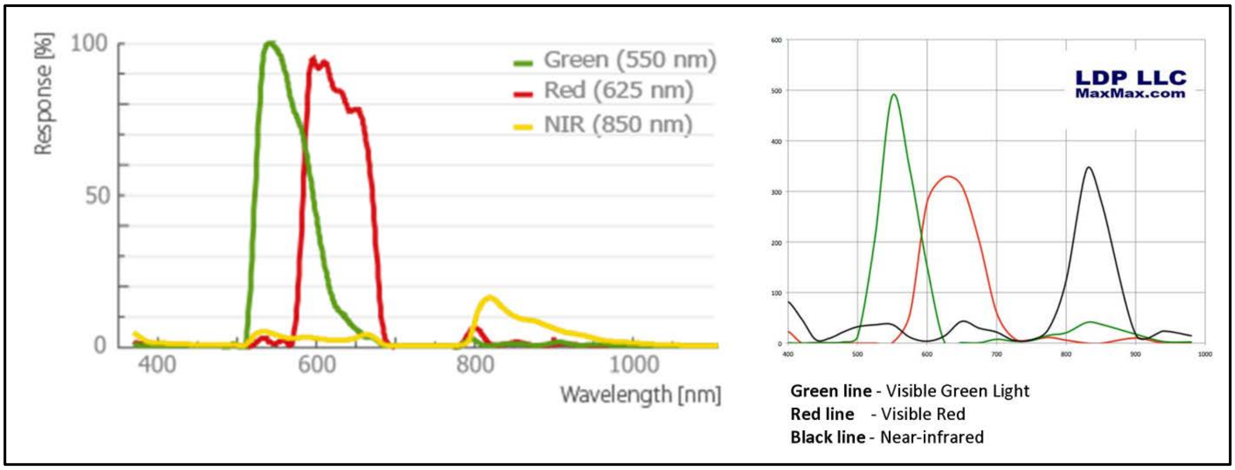

Figure 18: Examples of modified Canon cameras highlighting cross-talk (Sensefly, 2016; MaxMax, 2016).

Second, the wavelength location of the near-infrared band of a modified camera is often not located at the near-infrared plateau (beyond 0.8 µm), unlike satellite remote sensing instruments (e.g., Landsat-8). The location of satellite image bands, defined by their central wavelength and Full-Width-at-Half-Maximum (FWHM), is specifically chosen to meet the needs of monitoring applications and for atmospheric corrections. Landsat-8's near-infrared band is located at 0.85 – 0.88 µm to obtain measurements of reflectance at the spectral plateau where maximum light scattering occurs due to the internal cell structure of vegetation (Figure 2). The sensitivity of modified cameras is generally dependent on what filter was available by the manufacturer instead of specific monitoring applications. For example, some modified cameras are advertised as capable of deriving Normalized Difference Vegetation Index (NDVI) data for vegetation mapping, yet they acquire near-infrared measurements around 0.72 µm (i.e., 720 nm; Figure 19). This wavelength is located between the low reflection in the red region of the electromagnetic spectrum, and the high reflection of the near-infrared region (Figure 2). The transition zone between red and near-infrared reflectance is referred to as the red-edge region, and can be characterized by the steep increase in reflectance within this region (0.69-0.73 µm). The wavelength location of the steepest slope in the red-edge region (i.e., often referred to as the red-edge inflection point) shifts depending on a wide range of vegetation and environmental factors and has been correlated to the chlorophyll content of plants (Gates et al. 1965; Horler et al. 1983; Vogelmann et al. 1993). Nevertheless, NDVI data based on green light measurements (as replacement for the blocked red light) and near-infrared measurements captured in the red-edge region will not derive the same values or behave the same as NDVI data acquired at the scientifically- and industry-accepted wavelengths. This highlights areas of uncertainty about the compatibility of conventional remote sensing data outputs and RPAS outputs (e.g., imagery, vegetation indices). Standardized terminology is needed to describe RPAS outputs from modified cameras to clarify differences between sensor technologies. For example, vegetation indices lacking a red band and a band capturing near-infrared measurements at the red-edge should not be called NDVI (Hunt et al. 2011). Instead, such an index can be referred to as the GNDRE Index (Green Normalized Difference Red-edge) to acknowledge the inclusion of the green band (e.g., Green Normalized Difference Vegetation Index: GNDVI; Gitelson et al. 1996) and the red-edge band (Normalized Difference Red-Edge index: NDRE; Barnes et al. 2000).

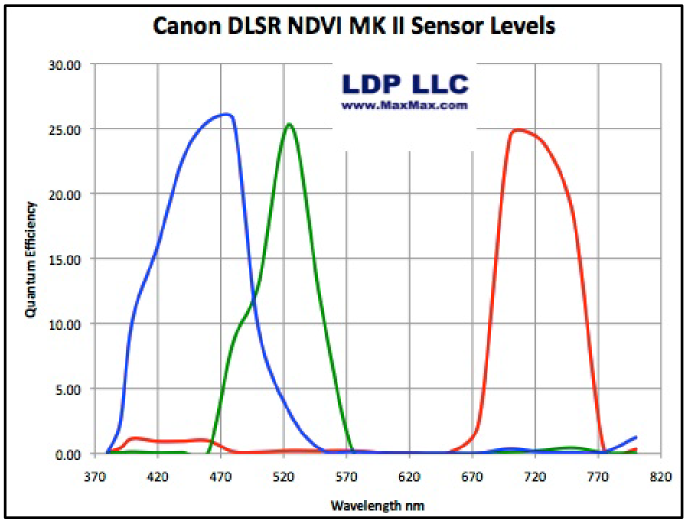

Figure 19: Modified Canon DSLR and the location of its near-infrared sensitivity at 0.72 µm (MaxMax, 2016).

Third, modified cameras are generally not calibrated with a stable monochromatic light source due to the cost (Hunt et al. 2010; Proctor & He 2015). Even if laboratory equipment would be available, the limited dynamic range of modified near-infrared cameras typically requires auto-exposure settings to prevent over- and under-exposures. The auto-exposure setting as well as differences in illumination conditions between overlapping images prevents the linear conversion of digital numbers into calibrated reflectance values due to changes in brightness in overlapping images (Hunt et al. 2011; Nijland et al. 2014). The relationship between camera brightness and reflectance has been shown to be highly non-linear, and exposure compensation is required to achieve improved correlations with ground observations (Ritchie et al. 2008).

Fourth, many filters that block red wavelengths to remain only sensitive in the blue, green, and near-infrared portions of the spectrum have low transmittance at near-infrared wavelengths (e.g., Figures 18 and 19; Hunt et al. 2011). The low transmittance reduces sensitivity and signal-to-noise, which impacts data quality. Systematic biases can be introduced during a band normalization process (e.g., calculation of vegetation index) when a vegetation spectral profile indicates a higher reflectance of visible band (e.g., green, red) than the near-infrared reflectance solely due to the lower sensitivity of the near-infrared band (i.e., opposite of Figure 2).

The combined effect of these considerations cumulates into the cautionary use of modified near-infrared cameras and their derived data. Their data cannot be reliably compared through time as near-infrared measurements of the same object may vary considerably due to angular variations in illumination conditions (e.g., morning, solar noon, afternoon) and atmospheric conditions (Nijland et al. 2014; Puliti et al. 2015; Rasmussen et al. 2016). This is especially the case considering the numerous variables that can influence brightness values (exposure, aperture, white balance, ISO settings). These sensors are not suitable for quantitative spectral analyses, thematic mapping applications (e.g., land-cover classification, feature detection), or temporal data mining (Whitehead & Hugenholtz 2014). Instead, their use is qualitative and can provide general insights into vegetation patterns (e.g., vegetated versus non-vegetated) that allow for within-field comparisons.

From an organizational perspective there are considerable differences between the images derived through calibrated satellite sensors and uncalibrated modified cameras. Considering known and unknown effects to imagery acquired with modified near-infrared cameras, care is advised when using this data. This is especially the case when imagery is used for regulatory reporting of environmental compliance. When consistent and reliable measurements are required across space and time, the use of purpose-built narrow-band cameras is recommended (Section 4.1.2.2).

7.4. Externalization of RPAS Services and Intellectual Property Rights

Due to their cost effectiveness, flexibility, and high resolution, RPAS represent a major shift in how, by whom and for what purposes geographic data is produced, accessed, and used. Producers and users of RPAS data should be conscious of the general duties of care and implied warranties along with intellectual property rights, and they are not immune from a regulatory or liability challenge. Organizations must be aware of the consequences that result when an independent contractor is hired to complete a RPAS mission instead of an employee. Under the *Copyright Act*, work conducted by an employee belongs to the employer if they are made within the scope of employment. As a result the employer is the owner of the intellectual property, who is free to reproduce, share, or alter the data depending on internal organizational standards. When the RPAS mission is conducted by an independent contractor (or sub-contractor), the work and therefore intellectual property is not automatically owned by the client even when it is within the scope of a single project.

RPAS-acquired still images and video can be transformed into a range of geospatial products, ranging from point-clouds to terrain models, and from resource inventories to land-cover classifications. The breadth of possible data formats, derivatives, and applications of data acquired through a single RPAS mission exceeds the dimensionality of other common geospatial image datasets (e.g., Landsat imagery), which along with the growth in the amount of data, number of actors, and interconnectivity of parties, will challenge relationships between contractor and client (United Nations 2013). For example, challenges arise when a client seeks to augment the data to further develop a value-added product or when an end-use or end-user of the data was previously not known (e.g., cross-agency monitoring of baseline conditions, permitting, and community outreach). It is therefore essential for organizations who contract or sub-contract RPAS services to ensure that end-user license agreements are in place that meet the needs of both the vendor and client(s) in terms of data reproducibility, data dissemination, and data alteration (e.g., terrain model derivatives). License arrangements should be specified, and agencies should seek to have acceptable data restrictions explicitly contained in a policy document instead of leaving it to individual employees with potential future implications (Amec Earth and Environmental 2010).

Knowledge of how RPAS contractors have structured and ascertain intellectual property rights is relatively sparse, and if these follow end-user license agreements of satellite imagery providers (Table 25), the uptake of geospatial data derived through RPAS may be hindered. This will especially be the case with sensitive datasets such as regulatory violations, wildlife observations and/or inventories, cultural or archaeological features, or other environmental parameters that affect regulatory compliance. As challenges regarding data ownership and use increase, new opportunities arise in metadata, standards, and data licensing to eliminate barriers to the open exchange of geospatial information and effective data integration.

Table 25: Example restrictions in an end-user license agreement of satellite imagery.

Any user or third party will not:
• publish, transmit, reproduce, create Derivatives of or otherwise utilize the Product in any form, format or media • merge the Product with any other data, information or content; • reverse engineer or otherwise attempt to derive the algorithms, databases or data structures upon which the Product is based; • distribute, sublicense, rent, lease or loan the Product • use the Product for the business needs of any third person or entity, including without limitation, providing any services to any third parties • remove, bypass or circumvent any electronic or other forms of protection measure included on or with the Product; • alter, obscure or remove any copyright notice, copyright management information or proprietary legend contained in or on the Product • otherwise use or access the Product or any Derivatives for any purpose not expressly permitted under this Agreement

Source: DigitalGlobe (2016).

Opportunities and challenges also arise as a result of the growing supply of, and demand for, cloud computing solutions for RPAS imagery. Cloud computing includes the delivery of computing power and data management as a service rather than a product, with as aim to decrease the costs of buying, installing, and maintaining computer hardware and software locally. RPAS acquire data in large quantities as a result of the high resolution sensors and the narrow flight-lines to cover the area of interest. To make the raw images usable, several data processing steps are required to calibrate, mosaic, and evaluate the imagery. The infrastructure required to accommodate the acquisition of highly detailed data over large areas and over time can be substantial for governments and businesses. With a continual focus on improving processing speed to accelerate analytics and predictive capabilities for rapid decision-making, cloud-based GIS solutions continue to see market growth (Markets and Markets 2016). The proliferation of specific RPAS cloud solutions further evidences this growth, with commercial products such as *DroneDeploy*, *Dronemapper*, *Datamapper*, *Autodesk ReCap 360*, and *Hexagon Geospatial GeoApp.UAS*, among others. These solutions lighten the burden of investments of hardware and software and increase organizational capacity in exchange for monthly or pay-per-use payment models. However, when data and services move to the cloud there are intellectual property risks and Chain of Custody for both cloud computing providers and users to consider.

One aspect of cloud computing is a direct result of its main advantage of being online; an unclear locality of hardware, software, and data. This results in a clients' data being stored and processed at one or more locations in the same or other jurisdictions at any given time, and whereby the client may not know where the data is stored or how it is processed. When data is stored in multiple (foreign) locations it may be less clear how intellectual property rights will apply to the end products produced by these services. Another aspect of cloud computing is the protection of sensitive or other corporate data. If the raw or processed datasets (e.g., aerial photos, ortho-mosaics) are part of a criminal prosecution the control of evidence is affected, which may result in a broken Chain of Custody that affects the admissibility of the evidence in court.

Before RPAS images or video are uploaded to a cloud solution, an organization should consider what duty of confidentiality and security is owed to both the user and the cloud service provider, and determine the best model for cloud computing (Hickling Arthurs Low 2012). Furthermore, the absence of a multi-national policy framework concerning intellectual property rights, liabilities, and warranties in cloud environments along with a lack of internationally accepted cloud computing standards for spatial data infrastructure (Hickling Arthurs Low 2012; United Nations 2013) may challenge the uptake of cloud-based RPAS services from a government or arm's-length agency perspective. This is especially the case for organizations seeking secure, long-term program sustainability with interoperability between data and applications and no vendor lock-in. It is therefore essential to review the terms of service before organizations migrate to cloud-based processing, and if possible, negotiate terms to cover liabilities and jurisdictional requirements. In any case, clients should have in place a contingency plan in the event that the vendor terminates the cloud storage service or makes major product changes that are incompatible with the organizational data structure. As challenges regarding the volume of RPAS data increase, new opportunities arise for flexible and interoperable cloud computing services that can specifically cater to organizations with high standards for confidentiality and security.

7.5. Occupational Health & Safety

Commercial and government organizations are committed to the health, safety, and wellness of its employees and provide a healthy and safe work environment that minimizes the risk of workplace injuries, accidents and illnesses. To protect employees, guests, and any person granted access to a workplace, an organization conducting RPAS missions will need to conduct its operation with strict compliance to all applicable federal, provincial, and territorial regulations:

- The federal *Aeronautics Act (Canadian Aviation Regulations)*,
- Provincial and territorial *Safety Acts* and *Safety Regulations*,
- Provincial, territorial, and business *Occupational Health and Safety Policies,*
- Provincial Worker's Safety and Compensation Commission/Boards *Codes of Practice*, *Hazard Alerts*, *WHMIS*, *Safety Bulletins*,

Failure to properly manage the use and workspace risk related to the operation and maintenance of the RPAS could result in fines and jail terms when convicted of a health and safety offence. With this in mind, RPAS do provide opportunities to reduce occupational health and safety (OHS) risk in a range of industries as: 1) employees are not present on-board manned aircraft and thus are not exposed to excessive noise, volatile fumes, or potential crashes, 2) employees have reduced exposure to heat/explosions, chemicals, noise, collisions, or struck-by/caught-in/caught-between hazards on the worksite grounds. The automation of dull, dirty, and dangerous tasks will improve OHS standards and worksite management (Shukla & Karki 2016).

The OHS risks associated with RPAS programs are mitigated through Transport Canada's regulatory approach, whereby the safety of all airspace users as well as people on the ground is of the highest priority. Therefore, when single or standing SFOCs are obtained, or when the exemption criteria for SFOCs are met, there is evidence that operators can conduct RPAS missions safely and that the organization and its employees are sufficiently trained and competent. Highly reliable fully autonomous UAS are currently not available from a technology or regulatory perspective, and organizations are only exposed to the OHS risks associated with the cognitive decisions made by skilled operators (Shukla & Karki 2016). Beyond the adherence to SFOC conditions, organizations can further mitigate risk by:

- Integrate Safe Work Practices (e.g., Field Safety Manual) to Standard Operating Procedures:
  - a hazard assessment for those who operate, teach, or maintain a RPAS
  - written work procedures for installation, operation, storage, and maintenance
  - stipulate the required conditions at the work site relative to RPAS capabilities
  - stipulation of required clothing and personal protection equipment
  - stipulation of safety or toolbox meeting guidelines for each RPAS flight
  - stipulation of RPAS safety checklist guidelines
  - stipulation of incident reporting guidelines
  - stipulation of journey manual guidelines
  - stipulation of first aid requirements
- Providing effective training, necessary licensing, documented proof of training
- Ensure effective review, tracking, and ongoing assessment of their use of RPAS

One significant element of personal safety when operating RPAS is the ergonomics of both the pilot-in-command and the visual observer. The main issues during the operation revolve around the prolonged tilting of the neck to maintain visual line of sight, and flight lines that are conducted too close to the orientation of the sun. In both cases there are means of mitigating, reducing and potentially eliminating the risk to the visual observer. For example, the visual observer may observe the flight at a distance in such a way to lower the large vertical angle with respect to the horizon while maintaining visual line of sight. Another mitigation technique is based on lowering the altitude of the flight plan. Flights should be planned with consideration made for sun angle and the location of the visual observer. Here flights should be timed to ensure that the RPAS does not cross between the visual observer and the sun.

7.6. Organizational Capacity and Program Sustainability

Organizations can benefit from the integration of RPAS technology regardless of business sector or departmental mandate. RPAS provide a medium to increase capacity to identify and quantity problems on site, extend monitoring to areas previously difficult to access, and a expand upon available site data that can be archived, reviewed on demand, and tracked over time. Regardless of the application there are both upfront and long-term costs attached to enabling staff or RPAS contractors. The up-front relate to the system (aircraft, ground station, flight planning software, image processing software, computer hardware, tools) and operator training (ground school, flight training). Long-term costs relate to RPAS insurance, regulatory administration, labour and parts, maintenance, hardware depreciation, and fuel (if not electric). Despite these costs, monitoring programs based on unmanned aircraft systems have much lower unit costs and cost per flight hour than manned aircraft (Brady 2013).

To accommodate a wide range of applications and reduce risk of program failure or unsustainability, RPAS programs should ideally deploy RPAS with attributes such as *interoperability* (i.e., output readily used in mapping software; multiple sensors), *modularity* (switching sensors/wings on-the-fly), and *redundancy* (i.e., increased reliability of sensor output). These attributes allow for flexible deployment to meet end-user information needs and will result in reduced complexity of maintenance procedures. The RPAS should be highly *automated* and *standardized* in terms of mission planning and mission control while in flight, and data processing to increase efficiency and effectiveness of the platform and reduce human and financial resource requirements. The systems should have high *survivability* through safe, automated take-off and landing capabilities and durable components that increase the likelihood of successful missions and reduce human resource requirements.

For a RPAS program or service to successfully delegate dull, dirty, or dangerous tasks in an efficient manner, a decentralized-centralized approach (i.e., multi-tier) is most often required in larger organizations. Such an approach establishes dedicated resources to gain the knowledge, skills, and experience to help with the transfer of knowledge to other co-workers or branches. For example, the success of a RPAS program typically relies on the balance between the benefits of decentralized capabilities near the sites of interest and the economies of scale opportunities that can be realized through a centralized approach. Flexible programs respond to divisional needs by establishing local in-house capacity close to the areas of interest, yet maintain a centralized "adequate management organisation" (Transport Canada 2015b) that provides a common approach to RPAS operations (e.g., documentation, regulatory procedures, standard operating procedures, best management practices, operations manuals, training programs, maintenance standards, insurance) and community outreach (e.g., Unmanned Systems Canada, geomatics working groups, academia). In large organizations, program approaches such as these reduce: 1) operational risks (e.g., people, process, technology, compliance, mandates), 2) financial risks (e.g., liability, program cost-effectiveness), and 3) reputational risks (e.g., direct or indirect impacts to the brand, image, reputation as a result of RPAS actions) through good governance practices and service standardization.

8. EMERGING OPPORTUNITIES

The industry surrounding unmanned aircraft and associated data processing solutions is rapidly growing and evolving both in Canada and across the world where advancements in robotics, computer vision, and geomatics technologies push the capabilities of RPAS. RPAS technology as a means to support data collection is already operational and available to a wide range of economic sectors as long as current regulations are abided by (Table 6; Riopel et al. 2014; Colomina & Molina 2014), and this medium will continue to serve both existing and new geospatial information users. The diversity of civilian RPAS applications will continue to grow as the Canadian Aviation Regulations adapt to the increased popularity and awareness of RPAS by end-users. To promote the use of RPAS, future efforts are focused on improvements in platform and sensor technology, beyond visual-line-of-sight regulations, earth observation and environmental research, data processing and management techniques, and data standards. Further opportunities arise for geomatics outreach through STEM (Science, Technology, Engineering, Mathematics) initiatives and community monitoring enablement.

8.1. Platform Technology

One of the most important advancements to promote the uptake of RPAS is the development of automated sense-and-avoid systems (Baillie et al. 2014). These systems will help to mitigate safety concerns and are a key component to beyond-line-of-sight operations. Several approaches are currently underway in two areas of technology: 1) sense-and-avoid capabilities for preventing collisions with other aircrafts or ground structures, 2) systems to maintain control of aircraft over extended distances. These approaches include the development of a *Low Altitude Tracking and Avoidance System* based on cellular networks and broadcasts of flight-paths to aviation authorities (LATAS 2016), advancing the capabilities of 3D sensors for obstacle avoidance in-flight (Ascending Technologies 2015), the inclusion of localized ground-based RADAR capabilities at the flight control station (Flight Global 2015), and improvements in command-and-control data links through Iridium satellite modems (Eggleston et al. 2015; Zmarz et al. 2015).

Beyond technologies that will enable safe long-distance flights, mission adaptability is another key area of improvement for RPAS technology. The miniaturization of micro-electro-mechanical systems will lead to improvements in the accuracy of onboard navigational sensors (GNSS, IMU), which will improve the exterior orientation estimation of images. The implementation of carrier-phase (L1/L2) GNSS technology will provide PPK or RTK surveying abilities, which will increase data accuracy and reduce fieldwork time as ground control points are no longer needed. Advancements in IMU technology will reduce the need for high imagery overlap and side-lap, from a current best practice of 70% to 80% (Section 6.3.2) to a 60% overlap and 40% side-lap (Mian et al. 2015). Parallel flight lines can be planned at wider intervals, which will extend the maximum flight length of RPAS and decrease the overall data volume. Together these advancements increase the agreement between image footprints estimated during flight planning and the actual ground coverage of each image (Whitehead & Hugenholtz 2014), therefore improving the reliability of complete coverage during the RPAS mission. These advancements will also shorten the turn-around time for data delivery which will further improve economies of scale of RPAS missions.

Survivability in is another key area of improvement, which is especially relevant for Canadian applications. The take-off and landing of a RPAS is often the most accident prone portion of a mission, and advancements in low latency laser altimeters will enable fully automated autopilot-controlled take-off and landing capabilities. Another key opportunity is the hybridization of vertical take-off and landing capabilities and the efficiency, speed, and range of fixed-wing RPAS, which will reduce operational footprints and increase portability. These advancements will reduce the need for human intervention and mission risk, especially in areas with tight landing zones (e.g., forests, inspections). As well, most turn-key solutions currently feature a low tolerance for freezing temperatures (Figure 8) that reduces the relevancy of RPAS for year-round environmental and infrastructure monitoring. Even in cases where the minimum operating temperature of a platform is rated at below-freezing temperatures (e.g., Sensefly eBee is -10°C), low temperatures (e.g., ≤ 0 °C) have been shown to increase battery consumption and shorten flights at high latitudes (Puliti et al. 2015). Therefore, improvements in cold-weather battery technology (e.g., battery warmers, battery cell tolerances) and autopilot tolerances and redundancy will expand the scope of RPAS surveys beyond the limited extents that can currently be covered. Improvements in winter capabilities is also an important advancement with respect to airspace safety (Szilder & Mcllwain 2012), as Transport Canada (2014d) normally does not permit operations in areas of known or forecasted icing. Advancements in anti-icing technology and the pursuit of manufacturers to obtain icing certification can prevent mission delays, especially in the Canadian Arctic and sub-Arctic.

8.2. Beyond Visual-Line-Of-Sight Operations

The development of automated sense-and-avoid systems will help mitigate safety concerns and will most likely result in a less restrictive regulatory environment in which RPAS missions can be extended over larger areas and at greater operating altitudes. Beyond-line-of-sight applications currently fall under the SFOC process (Section 5.1.1) and were not covered under the recently proposed amendments (Section 5.1.3). This means that for the foreseeable future these types of applications will require a SFOC. Transport Canada does permit operations beyond visual-line-of-sight flights if the operation occurs wholly within restricted airspace (e.g., Foremost Centre for Unmanned Systems, Alberta or Alma, Québec) or can be aided by ground-based RADAR systems (Transport Canada 2014d; Eggleston et al. 2015). However, because there is little guidance material or staff instruction the current framework is deemed too restrictive by RPAS operators (Baillie et al. 2014). Other countries, such as Australia and France, have already adopted regulations and standards for beyond visual-visual-line-of-sight operations (Baillie et al. 2014), and Transport Canada has indicated that a working group will soon complete standards for these types of operations for RPAS weighing less than 25 kg (Transport Canada 2015b).

Once enacted, beyond visual-line-of-sight regulations will realize the full economies of scale of RPAS missions. These regulations would come at an opportune time when combined with advancements in endurance (e.g., multiple hours), multi-sensor payloads (optical, LiDAR, SAR), real-time data transmissions systems, and data processing (Tables 5, 26). For example, these are the type of missions that can alleviate the high costs associated with infrastructure monitoring, natural resource inventories, and strip-transect wildlife surveys in Northern Canada, whereby

RPAS can respond to the flexible need for community monitoring (Aboriginal Affairs and Northern Development Canada 2013; Canadian Polar Commission 2014).

Table 26: Beyond visual-line-of-sight RPAS applications.

Protection of critical infrastructure	**Disaster Prevention and Management**
Monitor oil and gas pipelines	Night/Day Forest fire surveillance
Permafrost thaw detection on roads	Flood monitoring
Ice road monitoring	Floodplain mapping
Electricity grid thermal monitoring	Search-and-rescue
Environmental Protection	**Economic development**
Winter/summer wildlife surveys	Surficial geologic mapping
Coastal shoreline erosion monitoring	Forest inventories
Pollution detection	Land Surveying
Water Monitoring	Inspections

8.3. Sensor Technology

The continual expansion of small RPAS for mapping and remote sensing will result in new sensor developments that will better match the needs of end-users and scientists. The use of consumer-grade cameras leads to large perspective distortions, poor camera geometry, and a lack of spectral consistency (Puliti et al. 2015), which together limit the quality and therefore suitability of this imagery for quantitative (thematic) analyses and change detection (Whitehead & Hugenholtz 2014). Key sensor specifications that need to be addressed include the size and weight, image quality, sensor stability, signal- to-noise ratios, and the ability to record imagery across multiple wavebands simultaneously (Whitehead et al. 2014). Instead of increasing megapixels, one of the primary variables that can significantly improve data quality is an enlargement of the pixel pitch of the camera (i.e., physical size of a pixel on the sensor) (Haala et al. 2013). In addition, there are no standard tools available that can convert raw pixel values to reflectance values without requiring ground reflectance measurements. This complicates vegetation analysis by decreasing the precision of multispectral measurements and vegetation indices between flights as a result of illumination and atmospheric conditions (Whitehead & Hugenholtz 2014; Candiago et al. 2015). Therefore a need for onboard irradiance measurements as part of the data acquisition (Näsi et al. 2015) and integrated data processing (Parrot 2016) is highlighted. Advancements in sensor quality and calibration will foster the implementation of automated image analysis, which will increase the utility of RPAS across many sectors (Whitehead et al. 2014).

8.4. A Need for Additional Canadian UAS Test Sites

Even though beyond visual-line-of-sight regulations will be enacted at some time in the future, the market readiness of applications listed in Table 18 is limited due to the restricted access of appropriate case study sites (Figure 20). The large number of applications on the left half of Figure 19 highlights the need for regulatory and technology advancements to be solved in order for these applications to become operational. For example, over 50% of the Canadian UAS industry cite technological challenges and regulatory challenges that limit current RPAS operations (Baillie et al. 2014). These challenges can be solved simultaneously through greater access to experimental sites, which in return provides Transport Canada with data on which to base standards and regulations.

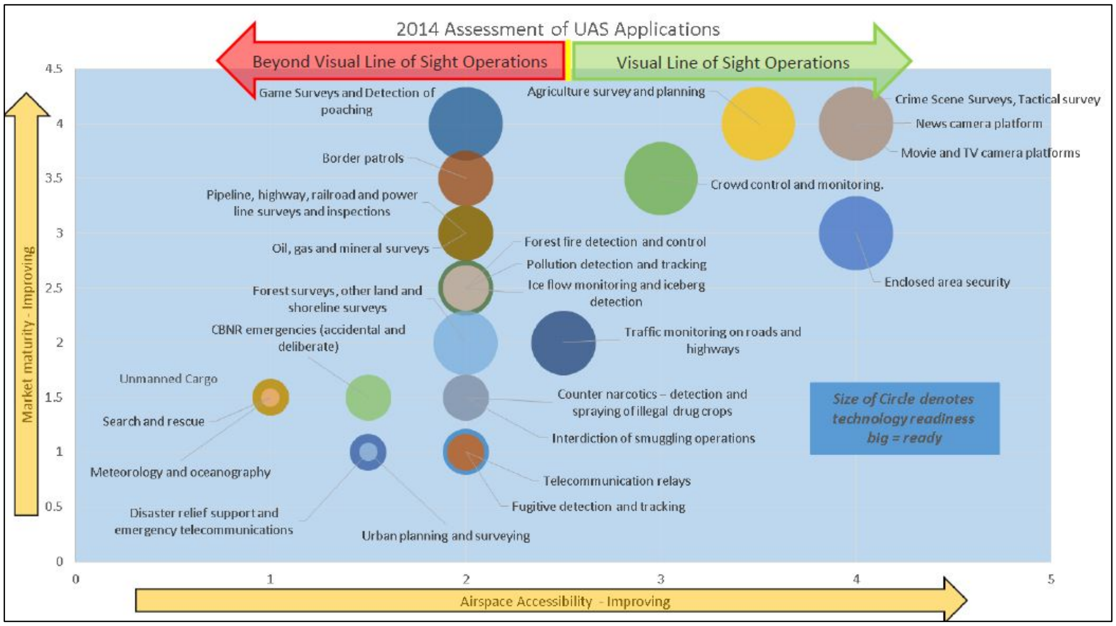

Figure 20: Market readiness and airspace accessibility of RPAS applications (Baillie et al. 2014).

Canadian UAS test sites create a positive feedback loop that will result in increased levels of research and development with respect to geomatics applications. Market readiness will improve through sensor testing and the design of accurate and standardized image processing protocols. To determine whether RPAS missions can alleviate the high costs associated with infrastructure monitoring, natural resource inventories, and strip-transect wildlife surveys, UAS test sites need to be: 1) sufficiently large and diverse to provide realistic comparisons to conventional methods, 2) located in current and expected regions of highest information demands (e.g., natural resources, climate change), and 3) located where the information interests intersect between multiple disciplines (e.g., pipeline monitoring and species-at-risk critical habitat).

There are four Canadian UAS test sites that provide a wealth of resources to advance the UAS industry, yet their spatial distribution is not representative of the diversity and composition of the Canadian infrastructure (Figure 21). Hence there are limited opportunities to develop and evaluate geomatics-related RPAS applications such as long-distance pipeline monitoring, pollution detection, and infrastructure asset management under controlled conditions at these sites. Neither do these four test sites reflect the topographical and ecological diversity of Canada (Figure 22), which challenges realistic comparisons between remote sensing-derived information and survey data through conventional means (e.g., wildlife surveys, forest inventories) (e.g., Section 8.7). In addition, as the test sites are located within the warmest climate zones it impedes the evaluation of RPAS performance under typical winter conditions for most of Canada, especially in the sub-Arctic and Arctic regions (Figure 22).

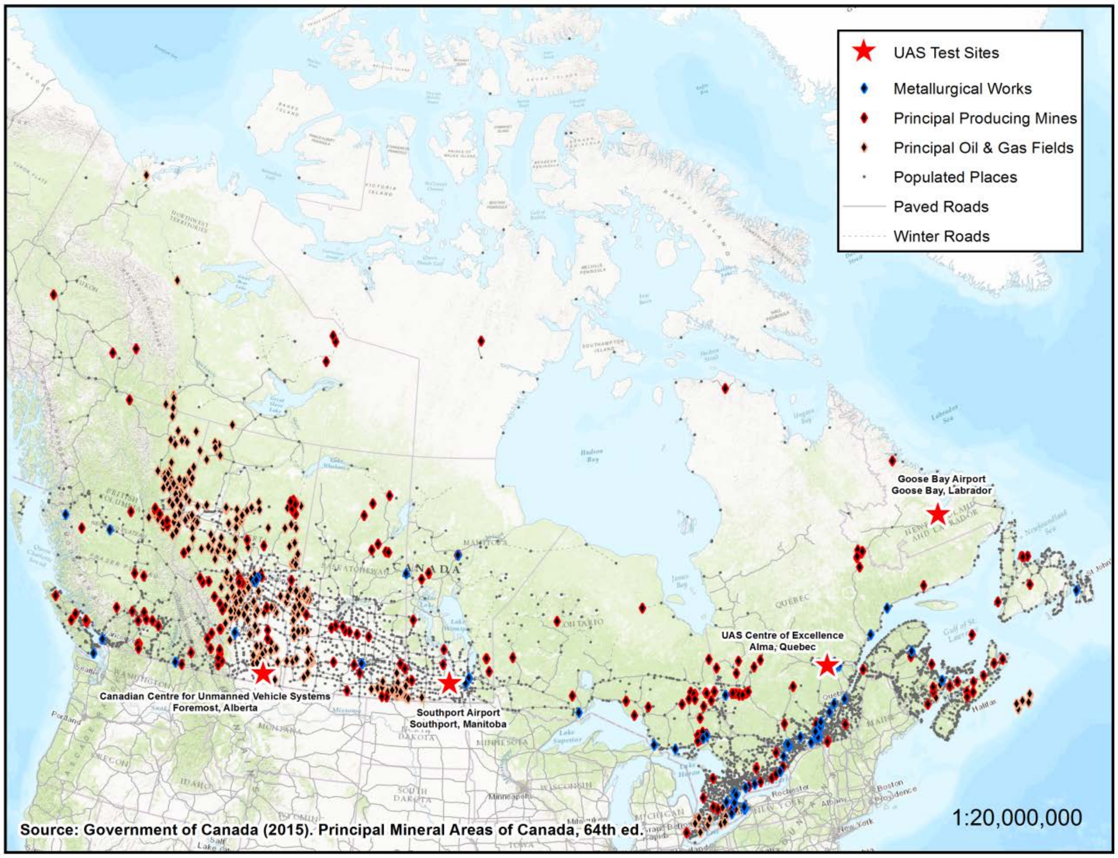

Figure 21: Spatial distribution of Canadian UAS test sites with Canadian infrastructure.

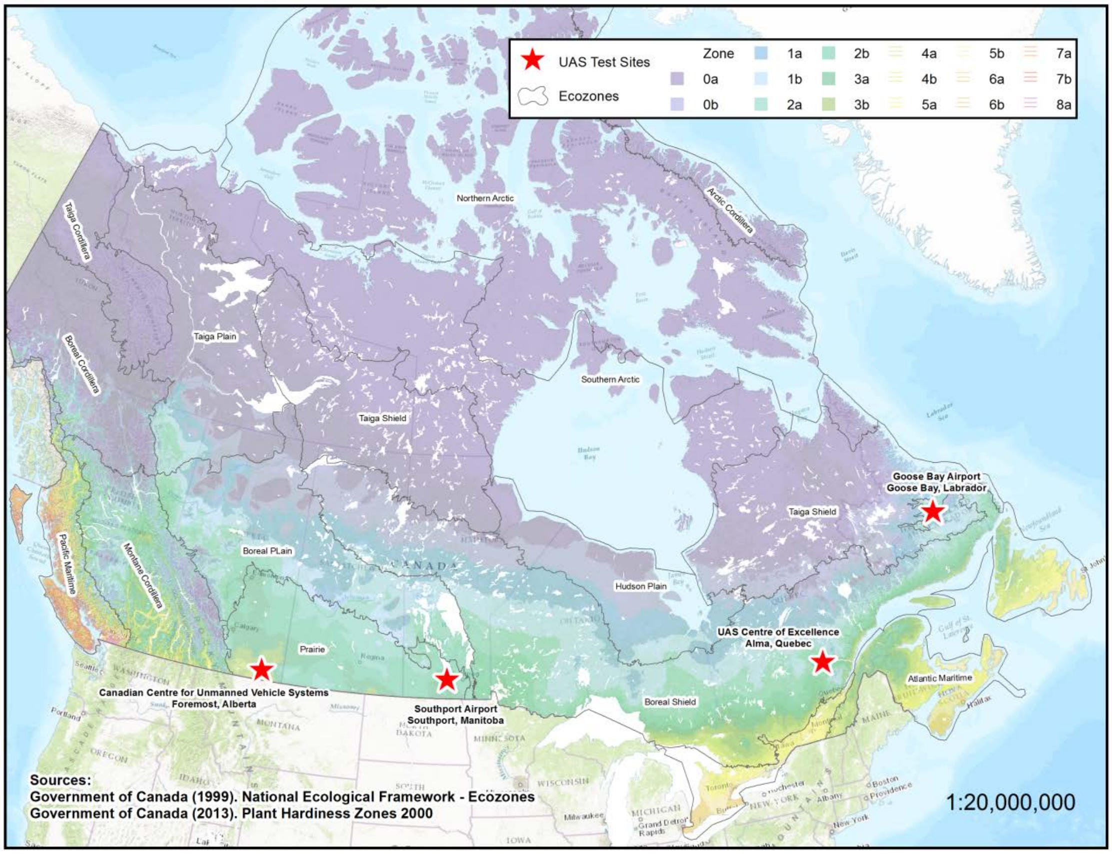

Figure 22: Spatial distribution of Canadian UAS test sites with Canadian Ecozones and Plant Hardiness Zones.

What follows is that additional UAS test sites are required for research and development and to advance the UAS industry for Canadian benefit. Similar to the U.S. Federal Aviation Authority (FAA) which has selected six test sites to represent the United States geography, climate, ground infrastructure, research needs, and airspace use from coast-to-coast-to-coast (FAA 2015), so should the number of Canadian UAS test sites increase to better reflect the economic, infrastructure, and environmental diversity in Canada. Hence strategically placed and road-accessible UAS test sites should be established in maritime regions (e.g., oil spill response in BC), mountainous regions, and northerly forested, environmentally sensitive, and/or mineral rich tundra regions (e.g., Northwest Territories, Nunavut). These can help meet research needs with respect to RPAS and sensor design, regulations, and image processing pipelines, which will simultaneously solve marketability and airspace accessibility challenges.

8.5. Data Processing and Management

A challenge for any remote sensing system is the extraction of meaningful knowledge that will aid in the decision making of end-users. RPAS provide an avenue to acquire imagery at a spatial resolution or a few millimeters (Mancini et al. 2013), and the flexibility of RPAS deployment can result in datasets of high temporal resolution. Conventional remote sensing procedures to obtain vegetation indices, image classifications, and statistical models were developed for airborne and satellite datasets with spatial resolutions ranging between tens of centimeters to hundreds of meters. These procedures were based on comparatively homogenous clusters of pixels that were well-suited for pixel-based analyses. However, the amount of detail in RPAS imagery represent new challenges due to high contrast differences of pixels, itself a result of pixels representing individual components of vegetation (e.g., leaves, branches) (Whitehead & Hugenholtz 2014). Combined with illumination differences throughout a RPAS scene as a result of a complex sun-sensor-object geometry and mosaic artifacts, this increased variability in spectral response will challenge pixel-based methods. As such a better understanding is required about the inherent complexity of RPAS datasets to identify robust spectral, textural, and structural parameters and new image segmentation approaches that can be readily integrated into data processing pipelines. Advancements in object-based analysis (Laliberte et al. 2010; Peña et al. 2013; L. Ma et al. 2015) are promising, and provide new opportunities for exploiting RPAS imagery for quantitative assessments. To further expedite these advancements by reducing costs, the availability of open source object-based analysis software programs should be stimulated.

Capturing high resolution data through RPAS also presents storage and computing challenges. For example, RPAS used for an earthworks survey will collect hundreds of individual images and gigabytes of data for final information products. Applications enabled by RPAS can be seen in the wider context of "Big Data" challenges and opportunities (Riopel et al. 2014), in which the spatial resolution, spectral resolution, radiometric resolution, and temporal resolution of datasets increase the complexity and data volume to an extent where it becomes difficult to conduct local processing and management (Y. Ma et al. 2015). RPAS deliver large ortho-mosaics and 3D point-clouds (hundreds of millions of pixels, points respectively) which challenges local infrastructure. Here opportunities for in-flight processing, data tiling, data streaming, and data compression arise that can mitigate the impact on local infrastructure (e.g., Sections 6.4). In addition, scalable and secure data warehousing solutions, on-site or in the cloud, will become increasingly important for data interpretation and management across government and industry sectors so long as ownership, responsibility, and control structures are in place. For example, in-flight data upload to a high capacity server can realize real-time or near-real-time data processing and delivery of information.

8.6. Data Standards

To accommodate these new opportunities, consistent standards and policies must be implemented to ensure interoperability and efficient management and sharing of location-based information (Riopel et al. 2014). RPAS are an advanced technology bringing new geographic data to many application domains, some who may not be familiar with geomatics data standards. RPAS are similar to other remote sensing systems where existing frameworks regarding data formats, metadata, and data quality are applicable (Percivall et al. 2015). However, the diversity of RPAS platforms along with the diversity of available sensors and data processing avenues (software packages, cloud solutions) are presenting challenges in the creation and maintenance of geospatial products. This diversity results in a lack of standardization at all levels, from sensor output characteristics, calibration methods, vegetation indices, and statistical models (Salamí et al. 2014). Furthermore, "Big Data" challenges drive the need for data streaming, compression, and analysis techniques that can result in proprietary data formats and vendor-controlled vertical integration of data processing and management services. These challenges limit format documentation and can negatively affect software interoperability, and result in format fragmentation and vendor lock-in.

Instead, a common approach based on Open Geospatial Consortium (OGC) and other international standard developing organizations is required to foster the uptake of RPAS across sectors and gain long-term benefits of their integration and compatibility (Aubert et al. 2012; Percivall et al. 2015). Data collected through RPAS requires systematic archiving that adheres to metadata standards (ISO 19115) to maintain discoverability over time, and need to be preserved in a matter to withstand obsolescence (GeoConnections & Hickling Arthurs Low Corporation 2013). The rapid growth of the RPAS sector therefore represent new opportunities for industry and geomatics agencies to establish and adhere to open standards that will enable interoperability and accessibility, which will further capitalize on the potential of RPAS (Natural Resources Canada 2015). To aid in these developments, the Canadian Council on Geomatics and Canadian Centre for Unmanned Vehicle Systems are well positioned to establish working groups to share experiences and establish a common position, similar to European National Mapping Agencies (e.g., Cramer et al. 2013).

8.7. Earth Observation and Environmental Modeling Research

Within the remote sensing discipline, the collection of field-data is typically one of the most costly steps during the research and development phase due to the costs of site access and the labour associated with the sampling protocols. Field data provides the statistical power to classify features or predict parameters of interest, and enable accuracy assessments that deliver important metadata from which the fitness of use of a dataset can be established. To obtain strong interpretations about statistical power and accuracy a valid sampling design, sample size, and relevant reference data are required. As sample sizes increase it reduces the risk of incorrect interpretations; however, adequate sample sizes are expensive, labour intensive, and time consuming (Congalton & Green 2008), especially in Canada's North due to its limited access (Aboriginal Affairs and Northern Development Canada 2013; Arctic Monitoring and Assessment Programme 2015). For example, typical rates for helicopter time in the Canadian Arctic are $2,000 per hour (Whitehead et al. 2013). One way to obtain additional sample data is the collection of airborne data through a less expensive protocol. For example, pan-Canadian LiDAR transects (Hopkinson et al. 2011) have been used to generate LiDAR-based predictions of forest stand attributes, which in turn have been used instead of ground plots to provide training and validation data for large-area forest mapping using satellite data (Wulder et al. 2012; Hall et al. 2015). In these instances LiDAR "plots" were used to scale local estimates to stand- and regional levels as each plot contains information about the terrain surface and three-dimensional canopy structure.

RPAS provide a similar potential for the spatial upscaling of environmental mapping procedures, albeit currently at a smaller geographical extent than LiDAR. RPAS data can link field-based ecological process-level data with geospatial data products derived from satellite remote sensing spanning a critical intermediate space and time scale that is essential for a comprehensive understanding for environmental modeling. For example, RPAS datasets can be combined with data of many aspects of ecosystems at local scales (e.g., 1 m – 100 m; permafrost, hydrological dynamics) and scale these to landscape level dynamics (e.g., 100 m – 10 km; lake beds, disturbances, habitats, watersheds). These can be scaled using satellite observations to meso- and regional-scale dynamics (e.g., 10 km – 1000 km) to further characterize larger regions and gradients. Similar scaling can be accomplished through time, where RPAS can scale between single ground observations and monthly satellite observations (e.g., Landsat-8) and acquire hourly, daily, weekly observations to understand fundamental processes and environmental changes. The decision to obtain a particular type of airborne data will be determined by a range of factors including cost, availability, detail and suitability. Data obtained from RPAS can bridge the gap between ground-based measurements and remotely sensed imagery from manned aircraft and satellite platforms, both in terms of image scale and image acquisition costs (Laliberte et al. 2011; Fraser et al. 2015). Even for large-scale mapping, RPAS datasets can be used for satellite data calibration and validation and can act as a natural extension of fieldwork to increase plot sampling and context (Figure 23; Li-Chee-Ming et al. 2015). Due to their cost effectiveness, RPAS represent an avenue to acquire data that can meet any organizational budget and support local environmental reporting. For example, RPAS can help acquire datasets to develop and optimize monitoring networks and provide baseline and trend data to support decision making in priority areas (Price et al. 2013; Canadian Polar Commission 2014).

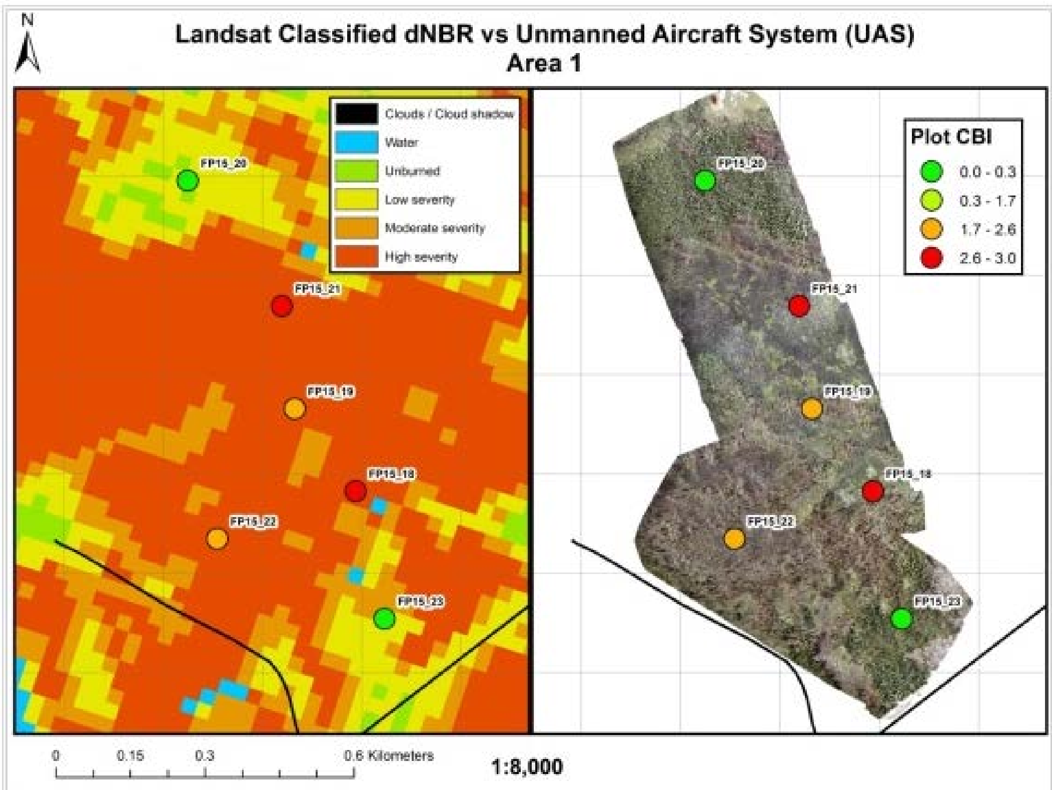

Figure 23: Assessment of forest fire burn severity using Landsat Normalized Burn Ratio and RPAS ortho-imagery. Point-data represent ground-based Composite Burn Index estimates (Source: NWT Centre for Geomatics, Canadian Forest Service, and Canada Centre for Mapping and Earth Observation.

8.8. Geomatics Outreach

Mapping data is a public asset and instrumental to problem solving and decision making (Canadian Council on Geomatics 2010). Due to the breadth of cost-effective applications and the low barrier for entry, RPAS technology represents an ideal platform to bring together producers and users of geospatial information. Hence it provides a key mechanism to promote the value of the geo community in order to improve opportunities, awareness, and understanding of its role in the Canadian economy, and promote opportunities for education in geomatics (Science, Technology, Engineering, Mathematics; STEM). Although geomatics datasets are used in web mapping services and education curricula, non-geomatics users may face difficulties visualizing objects or patterns in two-dimensional representations such as maps or ortho-mosaics during public outreach events (Arnold et al. 2000; Kuenzer et al. 2014). Hence the relatability and relevancy of even high quality geomatics work may be diminished from a public viewpoint as humans obtain visual cues in an oblique three-dimensional world. What follows is that any avenue to obtain faster and cheaper oblique imagery, video, and 3D models will help the communication and understanding of the work produced by the geospatial community. Even though RPAS may not be part of the original work or research, it can provide a rich environment of objects and phenomena that gives the presented work situated meaning wherein the provided context support the information being conveyed.

RPAS and ground-based robots have been used in a wide variety of STEM related activities for high school and university students (Eguchi 2015; ASPRS 2015b; Insitu 2015). One of the worlds' most well-known example of this is the "UAV Challenge Outback Rescue", held in Australia since 2007 (Arjomandi et al. 2009; Roberts & Walker 2010; Macke et al. 2014; Roberts et al. n.d.). The main objective of the challenge was a search-and-rescue type scenario where a RPAS would have to find a lost bushwalker in a 1.3 km by 2.3 km area and drop a water bottle to him. The impacts of this challenge were large, with well over 2400 university and high school team members involved in the events. The active and participatory style of learning enabled through RPAS included tasks such as the formulation of hypotheses, open-ended exploration and experimentation, as well as discovering the consequences of actions taken. These tasks approach the inquiry-based learning lauded by science educators (Bransford et al. 2000; Kubieck 2005; Gormally et al. 2009). As well, RPAS projects are usually set up to be solved in teams, solving science (geography, environmental), technology (training, building, repair), engineering (design), and mathematical (computer programming) during a project. In this context the teacher becomes a "wise enabler" who participates alongside the students to actively explore, experience, and engage directly with the ideas and practices inherent within STEM topics, instead of providing a passive lecture (Honey & Kanter 2013). These developments illustrate how RPAS can be a source of inspiration and engagement and a way to capture the curiosity and attention of students towards geography-related subjects. The user-friendliness and low costs of some RPAS also provide a low barrier for entry of teachers who are not overly comfortably teaching computer programming or other computer skills, or who feel they may not have the time or budget to teach new material. As a result, RPAS opportunities have led to influencing the career choices of students, the pursuit of scientific internships, and an expansion of a workforce that is technically equipped for the 21st Century.

8.9. Community Monitoring and Traditional Knowledge

Consistent monitoring of communities is important for administrative purposes and to increase knowledge on community changes over time (e.g., infrastructure due to climate change) and the sense of place. Aboriginal communities across Canada have long recognized the need to be actively engaged in the map-making process to share viewpoints, identify areas of importance, and to tell their own stories from being out on the land (Centre for Indigenous Environmental Resources 2010). For example, community mapping exercises are conducted for cultural inventories, consultations with industry and government, land-use planning, land selection, and resource management planning. Mapping tools are best administered as close to the decision maker as possible, however the high costs and funding challenges associated with the administration of a mapping program highlight the need for cost-effective and low-maintenance tools (Centre for Indigenous Environmental Resources 2010).

RPAS are ideal platforms to meet the information needs of communities due to the high spatial and temporal resolution capabilities, the insensitivity to cloud cover, the potential for 3D models, and their cost-effectiveness. As the data acquisition process is highly decentralized and straight-forward to implement, RPAS can potentially meet the needs for increased community involvement in local monitoring, especially in Canada's North (Canadian Polar Commission 2014). The ability of RPAS to acquire oblique and nadir photos and videos demonstrates how local communities can use the material for a wide variety of internal and external purposes (e.g., mapping, emergency management, site documentation, knowledge transfer, situational meaning). Due to this diversity of applications a community mapping program may realize a greater use and therefore payback for the investment, relative to satellite or airborne ortho-imagery for which specialized skills and end-user license agreements may be required (Centre for Indigenous Environmental Resources 2010). As community mapping exercises will likely take place in or nearby built-up areas, mapping offices may realize the easiest applications using Low Threshold RPAS (Table 11) according to the mission requirements presented in the Notice of Proposed Amendment (Transport Canada 2015b).

Local capacity building can take advantage of the low barriers to entry for RPAS operations, and when combined with targeted learning programs, local students (i.e., next-generation mappers) can be incentivized to study geography or mapping in community college and university in exchange for internships and other types of project-based service learning at local mapping offices (Centre for Indigenous Environmental Resources 2010; Sawyer et al. 2014). Although the benefits of RPAS for community monitoring are substantial, information about mapping efforts in Canada using this technology is sparse. The Wahnapitae First Nation in Ontario are experimenting with RPAS for regular updates to aerial photos (Anishinabek News 2015), and elsewhere RPAS are used to create "living digital maps" for the protection of wildlife and the conservation of forests in Guyana (United Nations Development Programme 2015), disaster response and risk prevention in Haiti (CartONG 2014), and animal inventories in Namibia (EPFL 2015). These efforts have shown that the integration of traditional knowledge with modern technology such as RPAS builds resiliency and capacity for local community members to lead their own projects, and to strengthen public awareness and capacity for environmental conservation, cultural preservation, and climate change adaptation.

9. CONCLUSION

9.1. Synopsis

The goal of this report was to synthesize scientific literature, operational experience, and policy recommendations and to help (non-)governmental organizations, private industry, and academia assess the operational requirements for developing geomatics programs and services based on RPAS. The sections closed knowledge gaps between organizations that have already begun to use unmanned technology within their programs with those that are intending to do so. In Canada, RPAS are a mature technology to support the development of geo-information products and services, and a large variety of operational platforms can serve a wide range of mapping and situational awareness applications. Autopilot technology and software for flight planning, flight guidance, and data processing is commercially available and production capable, and is highly automated. As a result RPAS can serve markets whose workforce has little aviation or photogrammetric experience. The ease of RPAS operations and the automated data processing and visualization techniques exemplify how programs and services based on these technologies can represent the entire modern geospatial information value chain (Natural Resources Canada 2015), with a focus on cost reduction, productivity improvement, and improved decision making.

The majority of operational RPAS applications are conducted with small RPAS and with consumer-grade cameras, over project areas not larger than 10 km^2. RPAS are suitable for a range of mapping applications, and at present the majority of operational applications are focused towards oblique still photography, video footage, and photogrammetric applications. RPAS can provide a price-performance level that falls between ground-based surveys and surveys from manned aircraft, and is highly competitive for many data acquisition projects. Surveying using RPAS is highly flexible in terms of scheduling, provides the highest resolution data available, and can achieve LiDAR-level accuracies (or better).

RPAS operators must abide by aviation, privacy, and intellectual property regulations. The current aviation regulations are relatively straight-forward with defined categories for exemptions and requirements for Special Flight Operation Certificates. Sometime in 2017 an amended regulatory framework is expected which will regulate unmanned aircraft not exceeding 25 kg and that are operated within visual-line-of-sight. This will likely reduce the need for SFOC's significantly, thereby reducing organizational risks and improving the ability to quickly respond to customer needs. From a privacy stand-point the collection of personal information from RPAS images or video footage are subject to the same privacy law requirements as any other data collection practice. With respect to geomatics applications, the acquisition of still imagery with consumer-grade small- to medium-format cameras mounted on a RPAS that is flying in public navigable airspace and away from buildings will not likely violate the right to privacy. The organizational risks associated with operations in the natural resource, agriculture, or forest industries are therefore considered low. Nevertheless, the geomatics industry has much to gain with a transparent approach through public notifications of RPAS missions, purpose specification, a designation of a point-of-contact, and appropriate data handling procedures. In addition, case studies highlighting how RPAS can alleviate dull, dirty, and dangerous work can foster public trust.

The development of a RPAS program or commercial service requires considerable resources, senior management support, regulatory compliance, and time. Best practices for project and program development, mission planning, field operations, and data processing were highlighted to reduce the chance for duplication of work between organizations, thereby decreasing business start-up timelines and increasing the sustainability of these services. Relatively straight-forward approaches exist to reduce operational, financial, and reputational risks based on good governance practices and service and data standardization.

The industry surrounding unmanned aircraft and associated data processing solutions is rapidly growing and evolving both in Canada and across the world. This medium will continue to serve both existing and new geospatial information users. To promote the use of RPAS, future efforts are focused on improvements in platform and sensor technology, beyond visual-line-of-sight regulations, earth observation and environmental research, data processing and management techniques, and data standards. Further opportunities arise for geomatics outreach in STEM (Science, Technology, Engineering, Mathematics) subjects and community monitoring enablement.

9.2. Recommendations & Knowledge Gaps

Rapid advances in RPAS-based monitoring have occurred in the last ten years. Previously limited to military applications and hobbyists, RPAS are now operational tools for geomatics experts, land surveyors, geographers, asset managers, and other professionals alike. Furthermore, RPAS are tools that can expand local community capacity and citizen involvement, and represent an exciting way to introduce science and technology to youth. With the continued evolution of platforms and sensors the range of applications for which RPAS are suitable will continue to expand. There are several needs for action to reach the full potential of RPAS-based geomatics applications in Canada. Some of these include improvements in hardware and software capabilities, where others including organizational courses of actions and filling knowledge gaps. In general, Canadian governments, industry, academia, and non-governmental organizations are well-positioned to further expand the RPAS sector for the economic, environmental, and social benefit of Canada.

- **Platform Technology**
  - Improve sense-and-avoid capabilities
  - Miniaturize micro-electro-mechanical systems for direct georeferencing and redundancy efforts
  - Improve fully automated autopilot-controlled take-off and landing capabilities (e.g., low latency laser altimeters)
  - Hybridize propulsion systems by merging VTOL capabilities with fixed-wing platforms (e.g., AeroVelco Flexrotor)
  - Improve the cold-weather performance of batteries
  - Improve battery recharging capabilities (e.g., solar panels on wings)
  - Improve the endurance and payload capacity of small RPAS through advancements in aerodynamics and battery, gas, and fuel-cell technologies
  - Establish de-icing capabilities

- **Sensor Technology**
  - Reduce the size and weight of sensors (e.g., thermal sensors, hyperspectral sensors, LiDAR, synthetic aperture RADAR)
  - Improve the availability of narrow-band multi-spectral sensors
  - Improve image quality, sensor stability, signal-to-noise of sensors
  - Establish on-board irradiance measurement capabilities
  - Establish an industry standard for measuring and documenting instrument performance
  - Standardize sensor outputs (e.g., image formats, metadata)
  - Improve the "hot-swap" capabilities of sensors

- **Data Processing and Management**
  - Improve interoperability using Open Geospatial standards and formats
  - Focus on metadata (software vendors and end-users alike)
  - Focus on collaborative, integrated approaches that define research objectives which are rewarding and considered scientifically valuable for end-users and remote sensing professionals alike
  - Focus on user-friendly tools and standardized procedures for spectral calibration of RPAS imagery for the calculation of reflectance
  - Investigate bi-directional reflectance challenges with respect to RPAS imagery acquisitions
  - Create user-friendly tools to merge telemetry information with video footage for MISB-compliant data management and viewing in GIS environments
  - Improve the availability of user-friendly object-based image analysis software packages
  - Improve in the standardization of object-based analysis approaches
  - Establish spectral and structural models and terminology designed specifically for RPAS to model vegetation characteristics and stresses
  - Expand the capabilities for in-flight offline or network-based data processing
  - Improve the understanding of ownership, responsibility, and control structures of cloud-based data processing and management solutions
  - Improve the understanding of typical end-user license agreement types used in the RPAS industry with a focus on intellectual property rights, data restrictions, and sensitive information (Chain of Custody)
  - Research approaches to solve environmental scaling challenges using RPAS

- **Regulations**
  - Establish consistency in the SFOC application process and assessment across regions
  - Establish consistency in the coordination with NAV Canada and Air Traffic Control
  - Finalize sub-25kg, within visual-line-of-sight aviation regulations (Transport Canada)
  - Clarify the Staff Instructions regarding the requirements and best practices for beyond visual-line-of-sight missions (Transport Canada)
  - Finalize sub-25kg, beyond visual-line-of-sight aviation regulations (Transport Canada)
  - Establish additional UAS test sites that expand upon the current availability

- **Geomatics Outreach, Sector Alliances, Capacity Building**
  - Promote the use of RPAS as an geomatics awareness tool for public outreach events and to provide relatable context for other geomatics work
  - Promote the use of RPAS to promote geography and geomatics in educational sectors (Science, Technology, Engineering, Mathematics; STEM)
  - Establish a Canadian RPAS in geomatics working group to share experiences, work towards standards, and establish common positions
  - Promote the use of RPAS for (northern) community capacity building, cultural preservation, and climate change adaptation as well as traditional knowledge integration.
  - Complete a systematic review of Canadian universities and colleges that use and research RPAS and determine Canadian competitiveness relative to other countries
  - Develop collaborative case studies that will assist stakeholders identify and address adoption challenges and determine return-on-investments
  - Complete a Canadian UAS strategy to highlight economic diversification opportunities

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11. APPENDICES

Appendix 1: List of available North American RPAS platforms

Appendix 2: Methodology RPAS Technology Overview

Appendix 1: List of available North American RPAS platforms

Company	Product [1]	Type	Max. Weight (kg)		Flight	Ceiling	Wind	Temperature (°C)		Cost
			Take-off	Payload	(min)	(m AGL)	(km/h)	Min	Max	(CAD)[2,3]
Aerial Data Systems	LDAP	Fixed	1.6	1.3	60	-	-	-10	40	-
Aerial Data Systems	MDAP	Fixed	-	1.8	40	-	-	-10	40	-
AerialX	NanoBird	Fixed	2.4	0.8	90	2000	85	-20	50	-
Aeromao	Aeromapper 300	Fixed	5.3	0.7	90	4500	40	-20	40	22,017
Aeromao	Aeromapper EV2	Fixed	4.5	0.5	60	4500	45	-20	40	17,201
Aeromao	Aeromapper Talon	Fixed	4.1	0.6	80	5000	30	-20	40	13,210
AeroVironment	Puma AE	Fixed	6.1	-	210	-	-	-10	40	-
AeroVironment	Raven	Fixed	2.2	0.2	110	4420	-	-10	40	-
Allied Drones	AW1 E-Star	Fixed	-	1.5	60	-	-	-	-	9,850
Altavian	Nova	Fixed	6.8	-	90	-	-	-10	40	40,000
Applewhite Aero	Invenio	Fixed	1.6	-	30	-	-	-10	40	-
Applewhite Aero	Milo	Fixed	8.0	2.0	90	-	-	-10	40	-
Applewhite Aero	Oculus	Fixed	3.0	0.7	180	-	-	-10	40	-
Brican Flight systems	TD100	Fixed	22.7	7.0	1500	4500	-	-40	45	600,000
C-Astral	Bramor C4EYE	Fixed	6.0	1.0	180	5000	75	-25	50	-
C-Astral	Bramor gEO UAV	Fixed	6.0	1.0	90	5000	75	-25	50	58,000
C-Astral	Bramor rTK UAV	Fixed	6.5	1.0	150	5000	75	-25	50	85,000
Delair-Tech	DT18 Big Mapper	Fixed	2.0	0.3	120	3000	-	-10	40	48,000
Delair-Tech	DT18 Crop Mapper	Fixed	2.0	0.3	120	3000	-	-10	40	44,000
Delair-Tech	DT18 Observer	Fixed	2.0	0.3	120	3000	-	-10	40	44,000
Delair-Tech	DT26X Crop Mapper XL	Fixed	18.0	4.0	150	-	75	-10	40	147,000
Delair-Tech	DT26X Observer XL	Fixed	18.0	4.0	150	-	75	-10	40	147,000
Delair-Tech	DT26X Big Mapper XL	Fixed	18.0	4.0	150	-	75	-10	40	147,000
Event 38	E384	Fixed	3.5	1.0	100	3960	35	-29	43	5,000
Event 38	E386	Fixed	3.3	0.5	75	3960	35	-29	43	10,800
ING Robotic	Serenity	Fixed	16.3	5.0	480	3800	-	-15	40	357,000
Insitu	Scaneagle (g)	Fixed	22.0	3.4	2400	4572	-	-	-	-
MarcusUAV	Zephyr	Fixed	-	-	180	-	-	-10	40	23,610
MAVinci	Sirius	Fixed	3.0	0.3	45	4000	50	-20	45	53,000
MAVinci	Sirius Pro	Fixed	3.0	0.3	45	4000	50	-20	45	71,000
Phoenix Aerial Systems	TerraHawk T-16	Fixed	8.0	2.5	80	17700	80.5	-60	60	110,786
Phoenix Aerial Systems	TerraHawk T-32	Fixed	8.0	2.5	80	17700	80.5	-60	60	149,071
PrecisionHawk	Lancaster	Fixed	3.4	1.0	45	4000	45	-10	60	28,500
Prioria	Maveric UAS	Fixed	-	-	60	7620	-	-10	40	-

Company	Product [1]	Type	Max. Weight (kg)		Flight	Ceiling	Wind	Temperature (°C)		Cost
			Take-off	Payload	(min)	(m AGL)	(km/h)	Min	Max	(CAD)[2,3]
Sensefly	Ebee	Fixed	0.7	0.2	40	974	45	-10	40	30,000
Sensefly	Ebee AG	Fixed	0.7	0.2	45	974	45	-10	40	30,000
Sensefly	Ebee RTK	Fixed	0.7	0.2	40	974	45	-10	40	60,000
Trimble	UX5	Fixed	2.5	-	50	5000	65	-10	40	66,000
Trimble	UX5 HP	Fixed	2.9	-	35	5000	55	-10	40	-
UASUSA	Recon	Fixed	5.4	2.3	60	4000	80	-10	40	-
UASUSA	Tempest	Fixed	9.1	4.5	240	5000	96	-10	40	-
UAV Factory	Penguin B	Fixed	21.5	10.0	1200	-	-	-25	40	-
UAV Factory	Penguin BE Electric	Fixed	21.5	6.6	110	6000	-	-10	40	-
UAV Factory	Penguin C	Fixed	22.5	-	1200	4500	-	-25	40	-
UAV Solutions	Talon 120 LE	Fixed	9.1	1.1	210	3300	-	-10	40	-
AeroVelco	FlexRotor(g)	Hybrid	20.5	1.5	2400	8000	-	-10	40	-
3D Robotics	Iris+	Rotary	1.7	0.4	16	-	35	-10	40	2,400
3D Robotics	Solo	Rotary	2.2	0.4	20	122	64	-10	40	1,374
3D Robotics	X8+	Rotary	4.4	1.8	15	-	88	-10	40	1,860
3D Robotics	X8M	Rotary	3.7	0.2	15	-	88	-10	40	7,605
4 Front Robotics	Navig8 Electric	Rotary	15.8	4.5	50	1500	72	-10	50	75,000
Aerial Data Systems	SDAP	Rotary	-	1.8	12	-	-	-10	40	-
Aerial Technologies Int.	AgBOT	Rotary	4.7	-	26	-	-	-10	40	25,000
AerialX	Hummingbird	Rotary	5.0	1.5	40	2000	90	-20	50	-
AeroVironment	Shrike VTOL	Rotary	-	-	-	-	-	-10	40	-
Aeryon	Skyranger	Rotary	-	-	50	4500	40	-30	50	120,000
Aibotix	X6	Rotary	6.6	2.0	30	3000	-	-20	40	42,000
Allied Drones	At44 Hornet Cam	Rotary	7.0	-	-	-	-	-	-	8,750
Allied Drones	EF44 Atlas	Rotary	-	2.0	60	-	-	-	-	-
Altavian	Galaxy	Rotary	9.5	-	30	-	-	-10	40	38,000
Bradatech	PX-Lite Plus 450	Rotary	2.2	-	18	-	-	-10	40	2,190
Bradatech	RX4-S Surveyor	Rotary	-	-	30	-	-	-10	40	5,990
Challis Heliplane	UAV E950	Rotary	25.0	15.0	60	6000	70	-5	35	48,500
Chaos Choppers	Chaos squad	Rotary	10.0	2.0	30	2000	80	-38	40	19,000
DJI	Inspire 1	Rotary	2.9	0.0	-	4500	-	-10	40	4,350
DJI	Inspire 1 Pro	Rotary	3.5	0.6	18	4500	36	-10	40	6,310
DJI	Phantom 3 Advanced	Rotary	1.3	0.0	-	6000	-	0	40	1,400
DJI	Phantom 3 Professional	Rotary	1.3	0.0	-	6000	-	0	40	1,770
DJI	Phantom 3 Standard	Rotary	1.2	0.0	25	6000	-	0	40	1,120

Company	Product [1]	Type	Max. Weight (kg)		Flight	Ceiling	Wind	Temperature (°C)		Cost
			Take-off	Payload	(min)	(m AGL)	(km/h)	Min	Max	(CAD)[2,3]
DJI	Phantom 4	Rotary	1.4	-	28	6000	-	-10	40	2,000
DJI	S1000+	Rotary	11.0	6.6	15	-	-	-10	40	7,645
DJI	S900	Rotary	8.2	4.9	18	-	-	-10	40	6,700
DraganFly	Commander	Rotary	3.8	1.0	45	2438	30	-15	40	37,142
DraganFly	Guardian	Rotary	1.5	0.4	10	2438	30	-15	40	11,002
DraganFly	X4-ES	Rotary	2.5	0.8	20	2438	30	-15	40	35,714
DraganFly	X4-P	Rotary	2.5	0.8	20	2438	30	-15	40	22,857
Flint Hills Solutions	320	Rotary	6.3	3.0	20	-	32	-10	40	-
Flint Hills Solutions	420	Rotary	13.1	5.4	40	-	48	-10	40	-
Flint Hills Solutions	520 (g)	Rotary	17.2	6.8	120	-	48	-	-	-
Flint Hills Solutions	620 (g)	Rotary	25.0	10.0	180	-	48	-	-	-
Hubsan	X4 Pro	Rotary	1.4	0.4	40	-	-	-10	40	2,150
Infinitejib	Orion 700	Rotary	12.0	4.0	20	-	60	-5	40	75,000
Infinitejib	Surveyor 300	Rotary	4.9	1.0	18	-	60	-10	40	32,000
Infinitejib	Surveyor 630	Rotary	11.0	4.0	25	-	80	-10	40	53,700
ING Robotic	Responder	Rotary	-	12.0	40	-	-	-10	40	47,000
Leptron	Avenger	Rotary	-	4.5	20	3658	64	-10	40	-
Leptron	RDASS 1000	Rotary	2.6	0.7	20	3048	56	-23	37	21,000
Lift Robotics	PM-81	Rotary	3.8	1.0	20	2000	40	-10	50	3,200
Lift Robotics	PM-81-M	Rotary	3.8	0.7	20	2000	40	-10	50	5,000
Lift Robotics	PM-81-T	Rotary	3.8	0.8	20	2000	40	-10	50	9,000
Lockheed Martin	Indago	Rotary	2.3	0.2	50	5500	-	-10	40	35,700
Microdrones	md4-1000	Rotary	6.0	1.2	45	4500	42	-10	50	58,000
Microdrones	md4-200	Rotary	1.1	0.3	30	2000	25	-10	40	29,000
Microdrones	md4-3000	Rotary	15.0	4.0	45	4000	42	-1	50	-
MosaicMill	Orthodrone	Rotary	4.0	0.8	38	-	29	-10	40	-
Phoenix Aerial Systems	AL3 S1000+	Rotary	11.0	7.0	10	4000	60	-10	40	18,714
Phoenix Aerial Systems	Alta	Rotary	13.6	7.6	10	4000	60	-10	40	22,921
Phoenix Aerial Systems	Scout S900	Rotary	8.2	4.9	15	4000	60	-10	40	15,393
Phoenix Aerial Systems	Vapor 55 (g)	Rotary	24.9	10.9	45	3048	48	-10	40	125,714
Prioria	Hex	Rotary	6.0	-	15	-	-	-10	40	-
Prioria	Hex Mini	Rotary	2.2	-	15	-	-	-10	40	-
REIGL	RiCOPTER	Rotary	24.0	8.0	30	4000	-	-5	40	-
Sensefly	EXom	Rotary	1.8	-	22	-	35	-10	40	45,000
SkySquirrel	Aqweo	Rotary	-	-	25	300	50	-10	40	34,286
Steadidrone	Mavrik M	Rotary	5.9	2.2	11	4000	40	-5	50	18,000

Company	Product [1]	Type	Max. Weight (kg)		Flight	Ceiling	Wind	Temperature (°C)		Cost
			Take-off	Payload	(min)	(m AGL)	(km/h)	Min	Max	(CAD)[2,3]
Steadidrone	Mavrik X4	Rotary	4.3	1.5	16	4000	40	-5	50	6,850
Steadidrone	Mavrik X8	Rotary	5.9	2.2	11	4000	40	-5	50	8,275
Steadidrone	Vader HL	Rotary	31.0	15.0	20	4000	40	-5	50	31,024
Steadidrone	Vader M	Rotary	18.0	6.0	40	4000	40	-5	50	33,200
Steadidrone	Vader X4	Rotary	14.7	4.3	50	4000	40	-5	50	21,100
Steadidrone	Vader X8	Rotary	18.0	6.0	40	4000	40	-5	50	25,400
Trimble	ZX5	Rotary	5.0	2.3	20	5000	25	-10	40	-
UAV Solutions	Phoenix 30	Rotary	5.5	0.9	35	3300	-	-10	40	-
UAV Solutions	Phoenix 60	Rotary	6.8	1.4	35	3300	-	-10	40	-
UAV Solutions	Phoenix 60LE	Rotary	18.2	-	50	3300	-	-10	40	-
UAV Solutions	Phoenix ACE LE Pro	Rotary	5.0	1.2	60	-	-	-10	40	-
UAV Solutions	Phoenix Ag	Rotary	4.5	0.9	40	3300	-	-10	40	-
Versadrones	Versa X6	Rotary	7.5	2.5	-	2000	-	-10	40	24,246

[1] (g) = Available to qualified governments only; export controlled.

[2] Prices generally reflect manufacturer's information. In cases where commercially off-the-shelf systems did not contain a sensor, the cost of the advertised compatible camera was included in the overall price (e.g., DJI Spreading Wings S1000+ and Zenmuse Z15-GH4 gimbal is compatible with the Panasonic Lumix GH4, yet the camera is not included in the manufacturer pricing estimate). Pricing information obtained from reputable geomatics industry magazine articles and through trade-show visits were included in cases where pricing information was not directly provided by the manufacturer or reseller.

[3] The pricing of some RPAS included a license to image processing software, whereas other manufacturers did not include this software in their pricing estimate. Hence the pricing information does not allow for a direct comparison of operational costs and is only meant as a relative indicator for initial budgeting estimates.

Appendix 2: Methodology RPAS Technology Review

The environmental scan includes an overview of the commercially available RPAS technology in North America. Specifically, the report reviews the current availability of RPAS that can be used in the geomatics sector (e.g., mapping, surveying, inspections) and the available sensor payloads that are associated with these RPAS platforms. A scan of RPAS platforms and sensor payloads was conducted in February 2016 to highlight commercially available systems that are "ready-to-fly" and fully integrated with respect to sensor payload and ground control station (i.e., operational systems). The report acknowledges that many Canadian companies specialize in RPAS components, control systems, sub-systems, and custom sensors or other payloads (e.g., Baillie et al. 2014). However, the scope of this technology review was limited to commercial-off-the-shelf systems for which no further integration of custom sensors was required, and which could be readily purchased or procured by Canadian organizations. Hence the data that was collected was limited to:

- Ready-to-fly RPAS (excludes hobbyist kits, custom builds, pre-orders, university research projects),
- RPAS with a minimum payload capacity of 0.2 kg and a maximum take-off weight of 25 kg. If the RPAS was unable to carry 0.2kg it was deemed unable to carry a sensor that would acquire meaningful geomatics data. If the RPAS was above 25 kg it was deemed challenging to operate under the current regulatory system,
- RPAS and sensors available through North American manufacturers, vendors, or official resellers,
- RPAS capable of executing fully pre-programmable grid survey missions and acquiring data for ortho-mosaic and Digital Surface Model production, or for general GNSS- or time-stamped video inspections. Cinematography and First Person View (FPV)-focused RPAS and sensors were therefore excluded.
- Sensors such as RGB cameras, converted-NIR cameras, NIR-only cameras, narrow-band multispectral sensors, narrow-band hyper spectral sensors, and LiDAR sensors, which were integrated in RPAS up to a total weight (platform + sensor) of 25 kg.

The data were compiled by examining existing reports to identify a list of North American vendors and resellers from which to gather the RPAS and sensor data, including lists reported in the following:

- Baillie, S., Meredith, K., Roughley, D. (2014). *Canadian Civil UAS 2014, an update to the 2008 report Canadian Market Opportunities for UAS: non-military applications.*
- Industry Canada. (2015). *Canadian UAV Company List-Directory*.
- Thompson, S., and Saulnier, A. (2015). *The "Rise" of Unmanned Aerial Vehicles (UAVs) in Canada: An Analysis of Special Flight Operation Certificates (SFOCs) from 2007 to 2012*.
- Geo-matching.com (2016). UAS for Mapping and 3D Modelling Product Catalogue. Accessed at: http://www.geo-matching.com/category/id64-uas-for-mapping-and-3d-modelling.html

In addition to the base list of RPAS companies, internet search engines, comparison websites, and industry news sites were used to further expand upon the list of companies and RPAS models. Those RPAS that were out of scope were excluded from the list. Most of the data was available through online specification sheets or informational brochures.

Companies were contacted using three different methods when data points were unavailable. First, a contact form at the respective website was used, second, an email was sent, and third a phone call was made to the nearest sales office. A message was left in case the phone call failed, and the data collectors called back again every few days for the duration of the review. Nevertheless, there were some data points that were unable to be filled. Another reason for missing data points was due to the manufacturers' unawareness of hardware limitations. Minimum and maximum operating temperatures and maximum wind speed tolerances are difficult to confirm without experimental data and suitable testing environments, and it is likely that official tests exceed the capacity of most manufacturers. The data on hardware limitations in this review should therefore be used with caution. Direct communication with manufacturers and real-world demonstrations are advised when organizations intend to purchase or integrate RPAS near the extremes of the operational envelope of RPAS.

All RPAS solutions offered sensors that can capture visible imagery. Most RPAS were designed to work with any commercial off-the-shelf consumer cameras (e.g., Sony, Canon), which can be readily modified to enable sensitivity in the near-infrared portion of electromagnetic spectrum. Hence an exhaustive overview of all possible visible and near-infrared sensors was impractical and not feasible for this report. Instead, the focus was narrowed to those sensors that were available as part of commercial packages.