New England Transportation Consortium (NETC)

NETC 18-3

Integration of Unmanned Aircraft Systems (UAS) Into Operations Conducted by New England Departments of Transportation

Task 2 Report

Identification of Current UAS Technologies and Support Systems

December 31st, 2019

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16. Abstract

Safety, accountability, and transparency are key guiding principles of State DOTs in their stewardship responsibilities. These principles are embodied in their mission areas to provide an effective and reliable transportation system. Unmanned aircraft systems technology is proving to enhance State DOT’s practices as an innovative and inexpensive solution that improves safety and accessibility, reduces cost, streamlines processes, improves workforce utilization and accelerates several transportation operations activities. A few studies have been conducted at the national level, but little guidance has been published on incremental steps to integrating UAS in various applications. The objective of this research is to provide guidance to New England State DOTs regarding effective practices when incorporating UAS into daily operations. The second phase of this research reflected in this Task 2 report provides a literature review, industry outreach, and an analysis on the market-ready hardware/software technology and support systems necessary to integrate UAS technology into the selected transportation applications. Subsequent phases of this research will investigate traditional workflows, address challenges with regulatory compliance, and develop procedures for the selected transportation applications.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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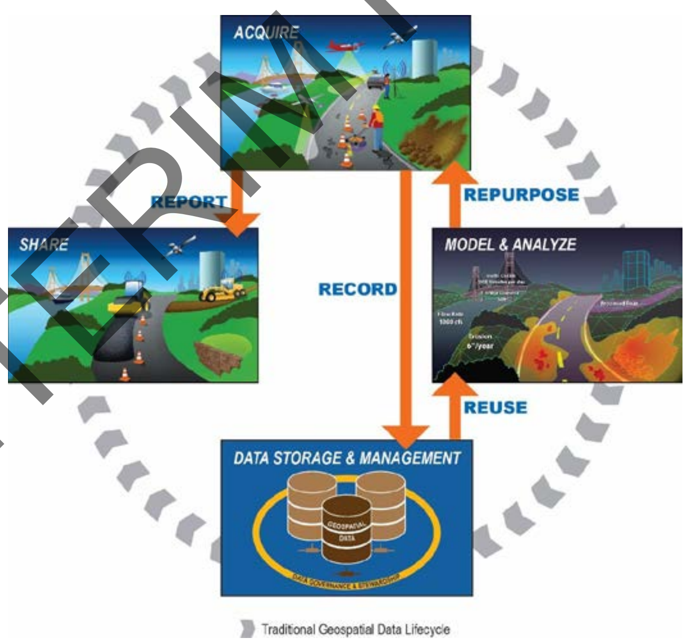
1.0 INTRODUCTION

Unmanned aircraft systems (UAS)[1] technology advancements have accelerated over the past several years primarily due to the popularity of the technology in support of the commercial industries. The Federal Aviation Administration (FAA) noted that approximately 12,000 commercial UAS were registered each month in 2019. This is slightly down from 14,600 registrations per month in 2018 and up substantially from 4,600 registrations per month in 2017 (Federal Aviation Administration, 2019b). As of December 2019, the FAA registered 420,340 commercial UAS (up from 277,000 in 2018) and certified 160,748 remote pilots (Federal Aviation Administration, 2019a). The FAA projects that 835,000 commercial UAS will be registered and 350,000 remote pilots will be certified by 2023 (Federal Aviation Administration, 2019b). The FAA projection models have been conservative, so it is possible that these projections will be met much sooner than 2023. UAS manufacturers will need to respond by increasing their market share through differentiation of products and services, price reductions, and innovation to attract investors.

The technological capability necessary to effectively enrich the traditional workflows of the selected transportation applications from Task 1 can be best understood using the geospatial data lifecycle (Figure 1.1) where collected UAS data can be used for many purposes, especially data-driven decision making. The UAS technologies currently available in the marketplace create workflow efficiencies and enable a deeper understanding of the operational environment. Defining a UAS technology strategy that encourages alignment with the geospatial data lifecycle ensures all necessary technical components are considered.

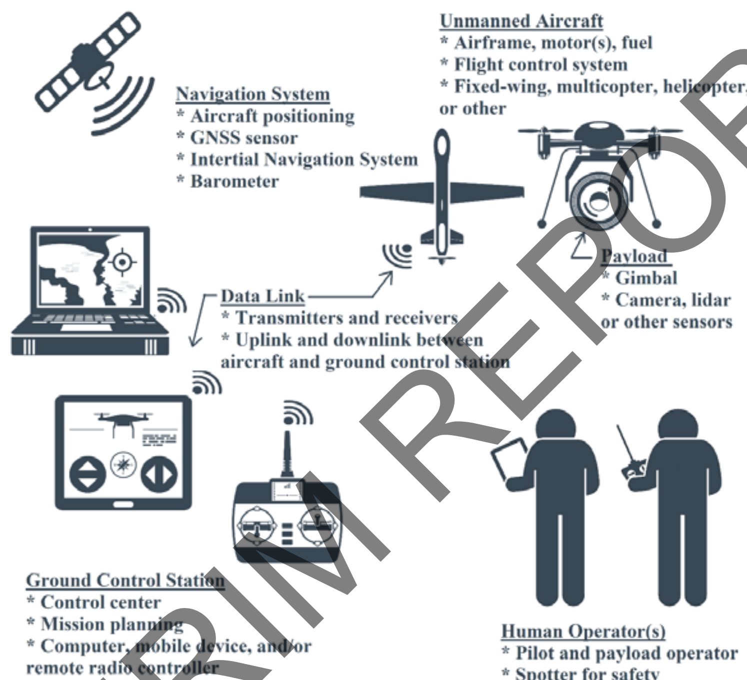


Original Illustration: © 2013 National Academy of Sciences

Figure 1.1. Illustration. Modified geospatial data lifecycle. Source:(Mallela et al., In-press)

[1] For the purposes of this research, UAS refers to small UAS as defined in Title 14, Code of Federal Regulations (CFR), Part 107 (Part 107).

While this report investigates and analyzes current market-ready technologies and support systems, it is highly likely that new technologies will enter the marketplace that further enable the use of UAS for the selected transportation applications from Task 1. The outcomes of this report are to bring awareness to the various technologies (e.g. hardware and software) and support system (e.g. safety, resource management, information technology (IT), and data governance) components, showcase a variety of technologies that could create long-term value for agencies depending the evolution of the marketplace, and bring clarity to the market-ready technologies available to the New England state DOTs. Figure 1.2 demonstrates the various components of a typical UAS operation.



© 2015 Dan Gillins

Figure 1.2. Illustration. Basic components of a UAS. Source: (Mallela et al., In-press)

2.0 HARDWARE TECHNOLOGY CAPABILITY

UAS hardware technology is the primary component of a UAS operation that creates the majority of safety risks and is the determining factor for regulatory compliance for UAS operations in the National Airspace System (NAS). It is important to understand the UAS hardware technology required for the selected transportation applications from Task 1 including aircraft configuration and avionics, sensor payload, ground control equipment, and safety enhancements.

2.1 Aircraft Configurations, Propulsion Systems, and Ground Control Stations

Commercial UAS can be categorized as consumer or professional grade aircraft distinguished by system durability, performance, pilot proficiency requirements, and sensor(s) capability. In general, consumer-grade UAS are less expensive with an average cost of approximately $2,500 (typically less than $10,000). Professional-grade UAS have an average cost of approximately $25,000 (some cost more than $100,000). The capability of consumer-grade UAS may be sufficient for many applications; however, certain applications with higher risk (e.g. bridge collapse or emergency response) or greater data quality specifications (e.g. higher accuracy or unique data outputs such as radar/thermal), may require a professional-grade system.

The aircraft configuration classifications fall into two categories including lighter than air and heavier than air. Table 2.1 showcases the airframe configurations available in the marketplace. Table 2.2 provides different propulsion systems used by UAS. Table 2.3 describes the different ground control system categories.

Table 2.1. UAS aircraft configuration classification (Ren et al., 2017)

Category	Classification	Definition	Examples
Airship	Lighter than air	Engine-driven lighter-than-air aircraft that can be steered.	• Challenger Aerospace aeroblimp
Fixed-wing Glider	Heavier than air	Lift generated by wing, but not depending principally on an engine for sustained flight, including powered gliders.	• Insitu ScanEagle • Silent Falcon EE • Black Swift S2
Fixed-wing Airplane	Heavier than air	Lift generated by wing, engine-driven propulsion, including weight-shift control and powered parachute aircraft, regardless of launch and recovery methods.	• senseFly eBee • Altavian Nova • Black Swift S1 • Saxon Viper M10 • Textron Systems Aerosonde • UAV Factory Penguin C • ELIMCO E500 • Embention F300
Rotorcraft Helicopter	Heavier than air	Lift and propulsion generated by engine driven rotor(s), principally depending on cyclic pitch for pitch and roll control, including compound helicopters with forward flight thrusters.	• AeroVironment Vapor • Alpha 800 UAV • SwissDrones SDO 50 V2 • Velos Rotors VelosUAV
Rotorcraft Multirotor	Heavier than air	Lift and propulsion generated by engine driven rotors, principally depending on differential lift from multiple rotors (normally fixed pitch) for pitch and roll control.	• DJI Phantom/Mavic/Inspire/ Matrice • senseFly albris
Powered-lift	Heavier than air	Capable of vertical takeoff, vertical landing, and low speed flight that depends principally on engine-driven lift devices or engine thrust for lift; and cruise flight that depends principally on wing for lift. May include gyrodynes.	• Wingtra One • xCraft X PlusOne and X2Q • FlightWave Edge UAS
Other	Heavier than air	Any other heavier than air aircraft configurations that may not fit or may not be derived from defined classes, for example ornithopters, or gyroplanes.	• Clear Flight Solutions Robird

Table 2.2 lists the various propulsion systems used for UAS. The most popular form of propulsion for UAS is electric battery given the weight restrictions and lower safety risks. However, electric battery is largely deficient with performance during cold weather, power transfer to propellers, and flight duration. This can be mitigated by using tethers or having additional batteries on hand. The other propulsion systems require some sort of fuel that not only increases the weight, but also increases the safety risk due to airborne flammable liquid.

Table 2.2. UAS engine propulsion systems (Ren et al., 2017)

Engine Category	Propulsion System	Examples
Piston	Propeller, ducted fan, or rotor(s)	• Saxon Viper M10 • Textron Systems Aerosonde • UAV Factory Penguin C
Turboprop/ Turboshaft	Propeller, ducted fan, or rotor(s)	• ELIMCO E500 • Embention F300
Jet	Jet (including bypass fan jet)	• SwissDrones SDO 50 V2
Electric	Propeller, ducted fan, or rotor(s)	• Saxon Viper M10 • DJI Phantom/Inspire/Matrice • senseFly eBee/albris • Intel Falcon 8+ • Wingtra One • AeroVironment Vapor • Altavian Nova

Table 2.3 describes the various types of ground control systems that allow for different levels of pilot control from direct control to autonomous control. Regardless of the transportation application, it is useful to have all these options. The more autonomy provided to the aircraft, the more upfront flight planning is required to ensure risk is managed appropriately. Also, it is important that all ground control systems employ manual override capability, which is imperative for any autonomous flight operation.

Table 2.3. UAS flight and operations control categorization. (Ren et al., 2017)

Category	Description	Notes
Direct Control (DC)	Remote pilot directly manipulates flight control via radio control (RC) link to achieve desired attitude, speed, altitude, and lateral path. Electronic stability augmentation systems may be utilized to reduce pilot workload and enhance safety.	High pilot action variability impact on trajectory. Ground control owns intended trajectory.
Mode Control (MC)	The remote pilot provides high level control commands via RC link, such as turn rate (bank angle), climb rate, target altitude, etc., while the manipulation of control being carried out by autopilot functions.	Reduced pilot action variability impact on trajectory. Ground control owns intended trajectory.
Flight Plan Control (PC)	The remote pilot provides an initial flight plan, and subsequent flight plan amendments during the flight via data link, while the manipulation of control surfaces	Eliminated pilot action variability impact on

Category	Description	Notes
	being carried out by autopilot functions following high level control commands generated by guidance functions.	trajectory. Ground control owns intended trajectory.
Autonomous Control (AC)	The remote pilot provides an initial flight plan and/or preprogramed or event driven uplink command to engage autonomous flight control logic that will generate flight intent or flight plan modifications based on sensor data to automatically carry out the flight utilizing guidance and autopilot functions.	Significant situation variability impact on trajectory. Airborne system (partially) owns intended trajectory.

Table 2.4 describes the various positioning systems available for UAS operations. Positioning may not be required for all transportation applications; however, it is an important consideration when evaluating programmatic capability. Global Navigation Satellite System (GNSS) Real-time Kinematic (RTK) positioning is advantageous when output data is required to be delivered quickly. However, GNSS Post-processing Kinematic (PPK) provides more control over positioning adjustments/quality. For GNSS-deficient areas, the use of inertial navigation systems (INS) helps with establishing the position of the aircraft and derivative data. The root-mean-square error (RMSE) of positioning systems is used to estimate positional accuracy and helps determine the suitability of a derivative UAS dataset. Therefore, the UAS positioning system is an important specification to consider when selecting a UAS for a particular application.

Table 2.4. UAS positioning systems. (Ren et al., 2017)

Category	Description	Examples
GNSS RTK	Positioning technology using an onboard GNSS receiver (L1/L2 bands) and a separate ground GNSS base station that transmits correction signals to the receive to compensate for positioning errors. This requires a radio link between the receiver and base station. Typical $RMSE_r$ (combined coordinate position) is 1-3 cm and typical $RMSE_V$ (elevation) is 3-5 cm. May require an additional surveyor to provide ground survey support.	• Trimble • Leica • Topcon
GNSS PPK	Positioning workflow using the GNSS log (i.e. RINEX) from the onboard GNSS receiver and the GNSS log (i.e. RINEX) from the ground GNSS base station to post-process the positions of the receiver and base station. This does not require radio link between receiver and base station. Typical $RMSE_r$ is 2-3 cm and typical $RMSE_V$ is 3-5 cm. May require an additional surveyor to provide ground survey support.	• Micro Aerial Projects V-map • AirGon Loki • EMLID Reach
Ground control points (GCP)	Ground control points are targeted locations on the ground. These targets are located in UAS data to orient and georeference data. The targets are measured using GNSS technology for improved	• N/A

Category	Description	Examples
	accuracy. Typical $RMSE_r$ is 1-3 cm and typical $RMSE_V$ is 2-3 cm. May require 1-2 additional surveyors to provide ground survey support.	
Integrated Sensor (GNSS/INS)	Combining GNSS positioning and INS technology, aircraft position and data quality are improved by reducing errors associated with aircraft movement. INS use a computer, motion sensors (accelerometers) and rotation sensors (gyroscopes) to continuously calculate, by dead reckoning, the position, the orientation, and the velocity (direction and speed of movement) of a moving object without the need for external references. This method is valuable in defining position in areas where GNSS is unavailable or denied. Typical $RMSE_r$ is 20-25 cm and typical $RMSE_V$ is 20-25 cm.	• Inertial Labs IMU-P • Advanced Navigation Motus • Inertial Sense µIMU • VectorNav 300 • NovAtel IGM-ADIS • NovAtel IGM-STIM • Any NovAtel INS • Trimble/Applanix APX15, AP20, AP40, AP60, AP80 • IXBlue • OXTs

2.2 Sensor Types

Passive sensors use the naturally emitting light/energy from the objects of interest to capture data. Passive sensor cameras collect visible (i.e. RGB), invisible (i.e. near-infrared, thermal, etc.), and hyperspectral imagery. UAS technology largely relies on passive sensors for collecting data. Depending on a particular use case, suitability of each type of sensor can be assessed using a predetermined set of criteria built from traditional methodologies and capabilities of aircraft/sensors. Most cameras available for UAS are consumer grade and non-metric, which requires a narrower cone angle and more sophisticated analytical methods than the use of metric cameras for precision measurements. Thus, users of non-metric cameras should investigate reproducibility of the principal distance and the principal point. However, the use of structure from motion (SfM) algorithms typically used for automatically tying images together present some uncertainty with generating surface models. (DELAIR, 2019)

Table 2.5 shows the different ground sample distances (GSD) achievable by certain camera resolutions from a 2/3" sensor camera with a 15-mm lens flown at specific altitudes above ground level (AGL).

Table 2.5. Common imagery resolutions and GSD at specific altitudes AGL (Propeller Aero, 2017) .

AGL	GSD in centimeters (cm) and feet (ft)			
Altitude	12 megapixel (MP)	20 MP	35 MP	50 MP
60 m (197 ft)	0.88 cm (0.029 ft)	0.70 cm (0.023 ft)	0.59 cm (0.019 ft)	0.50 cm (0.016 ft)
70 m (230 ft)	1.02 cm (0.033 ft)	0.82 cm (0.027 ft)	0.68 cm (0.022 ft)	0.58 cm (0.019 ft)
80 m (262 ft)	1.17 cm (0.038 ft)	0.94 cm (0.031 ft)	0.78 cm (0.026 ft)	0.67 cm (0.022 ft)
90 m (295 ft)	1.32 cm (0.043 ft)	1.06 cm (0.035 ft)	0.88 cm (0.029 ft)	0.75 cm (0.025 ft)
100 m (328 ft)	1.46 cm (0.048 ft)	1.17 cm (0.038 ft)	0.98 cm (0.032 ft)	0.84 cm (0.028 ft)
110 m (361 ft)	1.61 cm (0.053 ft)	1.29 cm (0.042 ft)	1.08 cm (0.035 ft)	0.92 cm (0.030 ft)

AGL	GSD in centimeters (cm) and feet (ft)			
Altitude	12 megapixel (MP)	20 MP	35 MP	50 MP
120 m (393 ft)	1.76 cm (0.058 ft)	1.41 cm (0.046 ft)	1.17 cm (0.038 ft)	1.00 cm (0.033 ft)

Active sensors use radar[2] [i.e. synthetic aperture radar (SAR)] or lidar[3] to capture data from onboard radio and light transmitters/receivers (see Table 2.6 for advantages and disadvantages of each sensor type). UAS equipped with radar and lidar sensors are potentially cost prohibitive for the majority of transportation applications if purchased outright by the agency. However, agencies are able to gain access to this technology through rental/lease agreements or through a consultant if it is determined that the use case requirements are more achieved more effectively with such technology.

Table 2.6. Common radar/lidar solutions and considerations.

Active Sensor	Advantages	Disadvantages	Use Cases	Accuracy
Lidar	Data capture day or night; quickly creates high-density point clouds; vegetation/fog penetration	Cost prohibitive; uncertainty with IMU compensation of multiple rotors	Topographic mapping; clearance measurements (overhead power lines or bridges);	Sub-centimeter (3D)
SAR	Data capture day or night; fog cover does not obscure objects	Not many commercially available solutions; cost prohibitive; varying terrain and vegetation distort phase angle of return signal	Wide area surface change monitoring (e.g. subsidence); slope stability monitoring;	~1 meter

Table 2.7 provides more detail on different sensors used for UAS operations as well as the required of the level of operational maturity. The operational maturity of a state DOT with specific sensors is driven by the ability to process and manage the output data from the sensors. Specialized knowledge and/or certifications may be required to fully demonstrate required proficiency in specific areas including thermography and photogrammetry. While the use of some of these sensors are nascent in a transportation context, the information infers enhanced situational capability that can be considered for future applications once proven.

Table 2.7. UAS sensor types and categories.

Classification	Category	Maturity Level Required	Description	Examples
Lidar	Active	Intermediate	Remote sensing technique pulsed laser beam(s) with the reflection time of the signal from the object	• Teledyne Optech Titan

[2] Radio detection and ranging

[3] Light detection and ranging

Classification	Category	Maturity Level Required	Description	Examples
			back to the detector being measured.	• Reigl MiniVux • Velodyne VLP • Velodyne Ultra
Echosounder	Active	Advanced	Remote sensing technique using soundwaves using single-beam or multi-beam emitting devices with signal returns from the object being measured.	• Any UAS tethered to vessel-mounted echosounder • Reigl BathyCopter
Radar - SAR	Active	Advanced	Remote sensing technique that produces high-resolution 2-D and 3-D images from radar reflections off the ground. SAR relies on radio or microwaves rather than visible light and can see through haze, clouds, and even thick forest canopies. SAR typically uses radio frequencies 1-12 GHz (L-band or X-band).	• SARAero SAR Unit • Imsar ONESAR • Brigham Young University (BYU) MicroSAR • Collins Aerospace MiniSAR • NuSAR • PicoSAR
Radar - GPR	Active	Advanced	Remote sensing technique that produces high-resolution 2-D and 3-D images from radar penetrations into the ground. GPR relies on radio or microwaves rather than visible light and can see through visible obstructions. GPR typically uses radio frequencies below 200 kHz (LF-band) with lower frequencies offering greater soil penetration depth, but may experience lower signal-to-noise ratios (greater interference potential).	• Radarteam Cobra Plug-in
Red-Green-Blue (RGB)	Passive	Novice	Imaging technique using the visible light (red, green, and blue) spectrum from sunlight reflected off objects. The signal is passive in nature and requires two overlapping images to render 3D measurements/characteristics of objects.	• DJI Zenmuse • FLIR Duo Pro R
Multi/ Hyperspectral	Passive	Intermediate	Multispectral imaging technique senses multiple (4-20)	• Headwall Nano-Hyperspec/Micro-

Classification	Category	Maturity Level Required	Description	Examples
			electromagnetic spectrum bands including visible light (7-bands: red, green, blue, cyan, magenta, yellow, and black), near-infrared (NIR), etc. spectrum bands from sunlight reflected off objects. Hyperspectral imaging technique senses 20+ electromagnetic spectrum bands including multispectrum bands and wider spectrum bands representing absorption, reflectance, fluorescence, etc. from sunlight reflected off objects. The signal generates spectrum data for each image pixel and is passive in nature, which requires two overlapping images to render 3D measurements/characteristics of objects.	Hyperspec/Co-Aligned VNIR-SWIR/High-Resolution Fluorescence • DJI Zenmuse RGNIR • MicaSense RedEdge-M • Sentera 6X • Parrot Sequoia+ • Sony QX1/QX10/R10C
Electro-optical (EO)/Infrared (IR)	Passive	Advanced	Hybrid remote sensing technique that combines visible and infrared spectrum data capture.	• FLIR EO/IR Mk-II • CONTROP STAMP/iSky • DJI Zenmuse XT2 • Colibri 2
Thermal	Passive	Advanced	Remote sensing technique that uses mid- or long wavelength IR energy. Thermal imagers are passive, and only sense differences in heat. These heat signatures (usually black (cold) and white (hot)) are then displayed on a monitor.	• FLIR Vue Pro • FLIR Duo Pro R
Hybrid	Active/ Passive	Intermediate	Remote sensing technique that combines active and passive sensors. Typical hybrid solutions on the market combine RGB sensors with lidar sensors.	• Delair DT26x
Gas Detection	Special Purpose	Advanced	Monitor air quality surrounding active scenes before entry, and industrial experts can perform inspections in hard-to-reach areas	• FLIR MUVE C360 • Black Swift S2 module

Classification	Category	Maturity Level Required	Description	Examples
Nephelometer	Special Purpose	Advanced	Detection of air particle size and distribution.	• Black Swift S2 module
Atmospheric Probes	Special Purpose	Advanced	Detection of atmospheric characteristics including pressure, temperature, humidity, and 3D winds.	• Black Swift S2 module
Radiometer	Special Purpose	Advanced	Microwave radiometer (L-band) for mapping of soil moisture in precision agriculture and sea surface salinity studies.	• Black Swift S2 module

UAS hardware and payloads should be hardened so that the critical components are protected from a broad range of environmental conditions. Ideally, UAS payload manufacturers should design and construct their hardware with MIL-STD-810 in mind to communicate to the consumers the level of protection the payload has with certain environmental conditions. Alternatively, International Electrotechnical Commission (IEC) protection classes (IEC 60529 Standard) is commonly used to communicate how capable a payload is with respect to certain conditions including equipment protection from foreign objects and water intrusion. (International Electrotechnical Commission, 2004) For example, the Riegl MiniVux lidar sensor has a protection class of IP 64, which meets protection against ingress of dust and splashing water.

IEC 60529 framework is fairly limited for the sensitivity of some UAS payloads, so knowing the capability of UAS payloads is paramount so process-oriented mitigation measures can be employed to reduce risks associated with other environmental conditions not covered by protection classes. For instance, the specific test methods under MIL-STD-810 applicable to UAS payloads may include low pressure (altitude), high temperature, low temperature, temperature shock, rain (including freezing rain), humidity, salt fog, sand and dust, immersion, acceleration, vibration, acoustic noise, shock, acidic atmosphere, freeze/thaw, and multi-exciter. (US Department of Defense, 2008) Since no commercial organization or agency certifies compliance with MIL-STD-810, manufacturers may take significant latitude with their tests, so consumers should verify (i) against which test methods of the standard the compliance is claimed; (ii) to which parameter limits the items were actually tested; and (iii) whether the testing was done internally or externally by an independent testing facility.

Regardless of how "rugged" a payload is designed and constructed, it is recommended to employ specific processes to ensure that the payload be acclimated to the environment in which it will be operated so no condensation builds up in the lens, etc. Insulation and protective apparatuses can also be investigated by agencies to protect components from environmental impacts and any negative impacts to performance.

2.3 Safety Enhancements

The UAS should have technology/support systems built in or capable of being integrated to enhance the safe operation of the flight. Safety enhancements play a vital role in ensuring the UAS and payloads are protected from crashing in case of any unexpected events during the mission. They also ensure safety of the participants and non-participants on the ground. These safety enhancements include ultrasonic obstacle avoidance systems (found in many DJI products) and ballistic parachutes, among others.

For instance, Parazero® offers SafeAir, an effective autonomous UAS safety system compatible with many inspection-specific commercial UAS (such as DJI Matrice 200 series) that comprises of independent sensors to continuously monitor flight data and detect any unplanned critical events. In case of an anomaly, the system triggers deployment of parachute and sets of an alarm to warn the bystanders on the ground following which the UAS descends to the ground in a controllable manner eliminating potential damage to the system due to the impact (Parazero, 2019). The ballistic parachute solution offered by Velos is another example that provides similar enhancement to a UAS helicopter to make the flight safer against unplanned events and crash landing (Velos Rotors LLC, 2019).

3.0 SUPPORT SYSTEMS

The UAS support systems required for the selected transportation application from Task 1 include safety/fleet/crew management systems, flight planning software, UAS data processing software, information technology (IT) infrastructure and security, and data governance.

3.1 Safety Management Systems

Safety Management Systems have four distinct components including a safety policy, safety assurance processes, risk management system/processes, and safety promotion, culture, and training. These components do not reside in a single enterprise system, rather it is a federation of systems and processes that are the essence of a UAS program. Policies and processes should be developed, stored, and maintained in a quality management system that is easy to use and accessible to all UAS program stakeholders.

Risk management activities include describing the UAS operational system, identifying hazards, analysis and assessment of the risks, and treating/mitigating the risks. The UAS operational system description includes a clearly defined/detailed mission, descriptions of the UAS operators and other affected stakeholders, description of the UAS equipment used, description of the procedures and policies that govern the systems' behavior, and a description of the operational environment. Identifying the hazards can be accomplished using a worksheet analysis tool to document the risks/hazards and links the hazards to controls and mitigation activities. The risk analysis includes consideration of credible effects, which are assumed combination of conditions that define outcomes. Note that less severe effects may pose a higher risk than the worst credible effect. The risk assessment is an evaluation of the composite of the predicted severity and likelihood of the potential risk/hazard. Risks can be mitigated is several ways and must be demonstrable to FAA. For example, mitigation measures may include identifying feasible risk management options, determination of predicted residual risk, definition of safety performance targets, and developing a monitoring plan that includes activities and methods to verify predicted residual risk. (Federal Aviation Administration, 2018)

UAS insurance is a common tool that commercial UAS operators use for mitigating risks of financial loss in the event of a mishap or incident. A public entity, such as a state agency, is distinct from commercial operators in that their inherent governmental functions are generally protected from its negligence.

However, if the public entity is performing proprietary functions, this protection may not be available, so insurance may be required to protect the public entity. As such, public entities should seek an interpretation of whether or not the use of UAS for a particular application is considered a governmental function. If the public entity uses UAS for proprietary functions or outsources UAS operations to consultants/contractors, the following insurance elements should be considered:

- General liability limits of $1,000,000 or more depending on risk level of UAS operation.
- Physical damage coverage/hull coverage for UAS units (including sensors) valued at greater than $2,000.
- Medical payments, premises, and non-owned UAS coverage for UAS under 55 lbs. that are rented or leased for less than 30 days.
- Personal injury coverage.
- Manufacturer products liability coverage.
- Cyber and data breach liability coverage.

Safety policies and processes used on a regular basis underpin all UAS program activities and create safety-oriented habits that are necessary for a successful and sustainable UAS program. Promoting safety and developing a culture of safety are necessary for robust safety management system. This ensures flight planning and operations are conducted instinctually with safety being the paramount driver of operational success. The following table provides a few commercial systems for facilitating UAS flight risk assessments.

Table 3.1. Commercial off the shelf software applications for UAS flight risk assessment.

Application	Description	Computing Model
Kittyhawk	Realtime UAS traffic, weather and flight advisories, review your mission risk profile before you fly. This helps quantify the amount of risk in a flight and apply common-sense policies to manage it. Also, Kittyhawk's Pilot Risk Assessment feature uses flight logs and UAS telemetry to compile a risk profile on each pilot based on their flight histories. Use this to get a high-level view on the overall risk profile of UAS pilots to better manage your UAS operations risk and liability.	Cloud
FlightSafety International	Flight Risk Assessment Tool (FRAT) for small Unmanned Aircraft Systems is a quick and simple utility to help remote pilots assess the potential risk of remote aircraft missions. FRAT App may be used to help assess risks to be encountered on a proposed flight and assist the UAS Remote Pilot in developing a strategy to mitigate such risk.	Cloud
SORA-based online tools	Guides through each step of the SORA process, show what safety objectives must be fulfilled depending on the planned operation and propose possible risk mitigation strategies (without the need to fully familiarize with SORA), and provide a preliminary feasibility analysis of the intended operation, supporting the actual development of a SORA-based risk assessment.	Cloud

The Specific Operations Risk Assessment (SORA) methodology (see Figure 3.1) is developed by the Joint Authorities for Rulemaking on Unmanned Systems (JARUS) to perform a safety assessment in support of UAS operations in the "Specific Category". This methodology is already accepted by several civil aviation authorities (CAA) around the world to demonstrate that the envisaged operation can be conducted safely. The SORA methodology includes a preliminary evaluation, ground risk evaluation, and an air risk evaluation to define specific safety requirements for a UAS operation (Joint Authorities for Rulemaking of Unmanned Systems, 2019). EuroUSC-Italia developed an online tool, SAMWISE (https://www.online-sora.com/), that walks through the SORA methodology. As SORA becomes more widely used, additional tools will likely be developed.

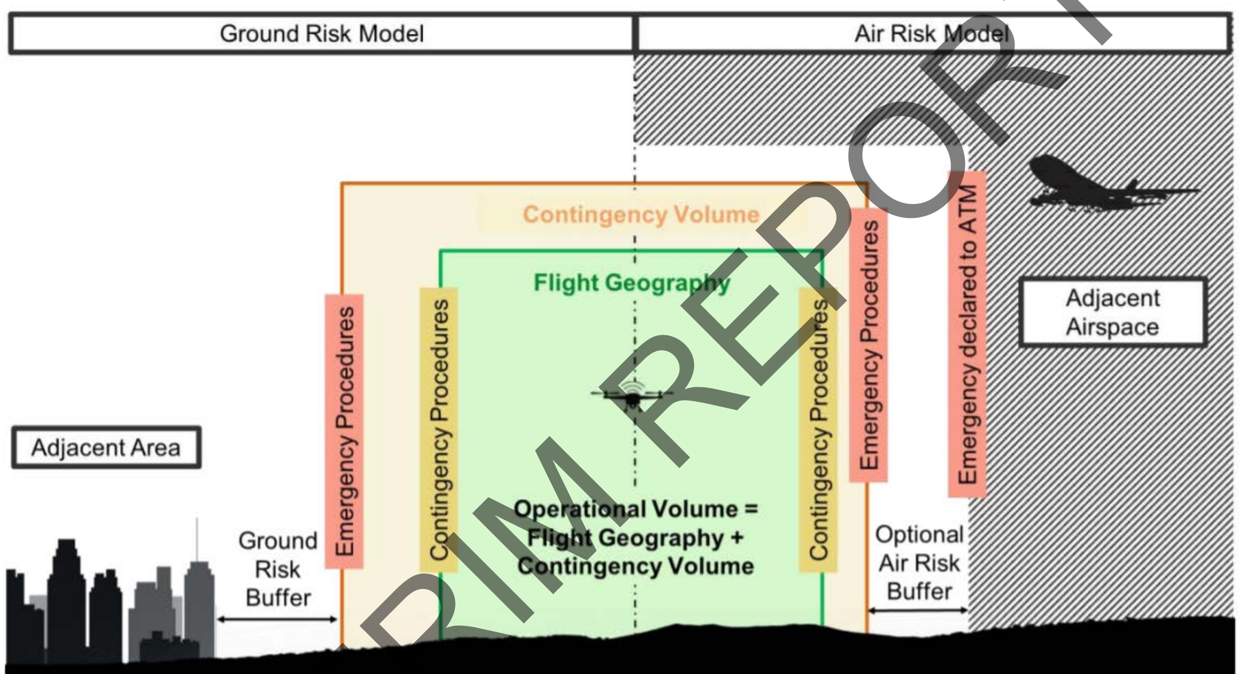


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Figure 3.1. Illustration. Graphical representation of SORA semantic model. Source: (Joint Authorities for Rulemaking of Unmanned Systems, 2019)

3.2 Fleet and Crew Management Systems

Fleet management systems encompass fleet utilization and maintenance characteristics such that the aircraft and associated systems are in proper working condition. The variety of aircraft available to public agencies also present unique considerations with respect to pilot proficiency and suitability. Certain aircraft are more suitable for applications than others and pilot proficiency with particular aircraft ensures maximum familiarity/dexterity with flight control as well as minimal risk of incident. Pre-flight and post-flight maintenance checks ensure airworthiness before the planned flight and addresses any repair needs after the flight. This redundancy ensures the proper care for the aircraft given its importance and criticality when operating in the NAS. There are many solutions available for enabling the inspection process including mobile-enabled applications for tablets and smartphones as well as cloud and desktop-based for personal computers. Table 3.2 provides examples of applications for fleet and crew management.

Flight crew management systems are often embedded into fleet management systems; however, the emphasis is on tracking workforce utilization, training program compliance (initial, proficiency, and recurrent), and credential management. It is vital that the flight crews are managed properly so that their proficiency is maintained for specific applications and they develop appropriate practices that empower a "safety-first" culture.

Table 3.2. Software applications for UAS fleet and crew management.

Application	Description	Computing Model
Kittyhawk	Manage the fleet by assigning missions, creating workflows and monitoring the activity of operators, aircraft and assets. Replace spreadsheets and file folders with one single system of record for all UAS activity.	Cloud
DroneLogBook	Plan, manage and track UAS flight operations to help maintain regulatory compliance and better manage their operations.	Cloud
Skyward	Log pilot information, flight hours, authorizations, aircraft, and projects in one place, Skyward is a complete system of record and provides transparency for managers and legal teams.	Cloud
DroneComplier	Manage entire UAS operation with one intuitive, enterprise-grade solution. Plan and assign your UAS fleet to flights, track pilots, batteries and gear, customize safety plans and automate your compliance obligations with the FAA.	Cloud
Airdata	Automatically upload flight logs, get immediate visibility to the performance of your aircraft, identify potential issues with your flight, eliminate manual recording of flight information, and reduce data entry errors.	Cloud
Spreadsheet (or standalone electronic file)	Manually manage UAS fleet and crew information for supporting resource allocation and performance reporting. Limited to no automation of data field calculation. No interface with other systems. Cloud computing is used mainly for file storage as opposed to data exchange/analysis.	Desktop Client/Cloud
Paper	Physical media used for managing UAS fleet and crew information.	N/A

3.3 Software and Interfaces

The dominant limitations of software or computers is processing power and data storage. UAS data (imagery, video, and point data) is resource intensive given the size of the dataset(s). A single UAS flight can generate several gigabytes of data, so sustainable solutions for data processing and storage are critical to the success of a UAS program. The longer flight times become, the more these limitations will be exacerbated. In order to process these large datasets using semi-automated techniques using computer vision algorithms such as structure from motion (SfM), the computer systems should be bolstered in a few key areas including a quad-core+ processor, 500+ gigabyte solid-state hard drive, 16+ gigabyte random access memory, and a strong graphics card.

There are three models for processing UAS data including cloud-based automated processing, desktop processing, and expert processing (internal or consultant). The following table shows some general characteristics of these categories and their respective ratings.

Table 3.3. Characteristics for different computing models. Adapted from Karpowicz, 2018

Characteristic	Cloud-based automated processing	Desktop processing	Expert Processing (internal or consultant)
Accuracy	Low	High	High
Reliability	High	Low	High
Simplicity	Simple	Very complex	Simple
Flexibility	Rigid	Very flexible	Very flexible
Turnaround time	Fast	Slow	Slow
Cost	Low	High	Medium
Suitability	General monitoring; quick, low-accuracy maps	Poor internet connectivity; sensitive data; unusual projects	High-accuracy land surveying and mapping

Software systems play a crucial role in managing various stages of an UAS mission ranging from flight planning and control, data collection, and post flight data processing. The widespread adoption of UAS across several industrial sectors have led to creation of software solutions of different types to meet the needs of customers and the specific requirements of applications.

- **Cloud vs. Desktop Computing**: Stand-alone desktop solutions offer the best capabilities of data processing in terms of accuracy and flexibility of methods available for analyzing the data thereby yielding multitude of outputs. While cloud-based solutions offer promising results in terms of variety of outputs, they are usually less accurate and simple to enhance real-time data sharing and collaborative teamwork. This feature will particularly assist tasks that have rapid turnaround. Table 3.4 provides list of commercial solutions classifying them as desktop client or cloud-based solution
- **Proprietary vs. Open Source:** Post flight data processing solutions can be proprietary or open-source platforms. Most of the flight planning and post flight data processing solutions commonly used for industrial applications are often proprietary as they offer variety of methods, scale to large datasets efficient, and has established customer support for dealing with implementation challenges and product upgrades. Most of the software identified in Table 3.4 are commercial and priced. While not uncommon for industry applications, open-source platforms are most commonly used for recreative or research-related initiatives as they usually focus on highly advanced option for photogrammetry and structure from motion. Examples of open source platform include COLMAP, Meshroom, MicMac, Regard3D and VisualSFM among others.
- **Application Programming Interfaces (APIs) and Software Development Kits (SDKs)**: APIs are tools that are used to interact with an external service using a set of simple commands to add specific functionalities to the software platform, while an SDK is a set of tools that are used to develop customized applications for a specific platform. Many of the commercial UAS manufacturers are enhancing the functionalities of their software by providing the option incorporate external APIs and making available SDKs for programming and customization in their

platform. As an instance, DroneDeploy offers powerful APIs to enterprise developers to integrate the collected and processed data into their own applications and services (DroneDeploy, 2019). DroneDeploy's SDK comprises of four nodules – UI toolkit, Datastore, Functions, and triggers – to enable customization and automation of some of the complex use cases (DroneDeploy, 2019)

The following tables describe the various systems used for multiple phases of UAS operations (Table 3.4), UAS flight planning (Table 3.5), UAS flight operations and control (Table 3.6), and UAS data processing (Table 3.7). The computing model for each application is provided for reference. There are countless options, so evaluating suitability and compliance with IT policy is left to the individual state DOTs. In some cases, the preferred software will require adjustments to existing IT policies, which should be outlined in the business case.

Table 3.4. Commercial off the shelf software applications for multiple phases of UAS operations.

Application	Description	Phase	Computing Model
Pix4D	Suite of photogrammetry software widely used by many industries such as surveying and construction for UAS mapping	Flight operations/ Post-flight data Processing	Desktop Client/Cloud
Lockheed Martin Hydra Fusion	Real-time Geospatial Information System that simplifies information by fusing this data to create a 3D world presentation that gives immediate 'in context' information. The stand-out feature of Hydra Fusions Tools is its ability to simultaneously localize and map (SLAM) incoming video or still image feeds from the aircraft while it flies. These images are incrementally matched up, stitched together, and geo-registered resulting in an immediate and immersive 3D reconstruction.	In-flight and post-flight data processing	Desktop Client
Kittyhawk	Kittyhawk mobile apps help prepare for a safe and successful mission by checking airspace and weather, running a safety assessment, and getting necessary authorizations. Flight logging happens automatically. Media is securely transmitted to business apps. Operators experience maximum situational awareness. Sometimes there is no time to wait and see what a UAS saw after the fact. Create a live video stream of what the UAS is seeing and share to anyone on the team, complete with conference-call audio. A powerful tool for incident response, training and safety.	Flight planning, flight operations, and in-flight data processing	Cloud

Table 3.5. Commercial off the shelf software applications for UAS flight planning.

Application	Description	Computing Model
AirMap	Suite of photogrammetry software widely used by many industries such as surveying and construction for UAS mapping	Cloud
Esri ArcGIS	Geographic information system used for generally mapping out area of interest and understanding site conditions that may impact flights such as elevations, vegetation, structures, and airport locations.	Desktop Client
iFlightPlanner	Online and mobile-enabled flight planning application for planning flight routes using IFR/VFR aviation charts and Google Maps; viewing enroute aviation weather, translated METARs and TAFs, TFRs, and graphical AIR/SIGMETs; receiving certified weather briefs, performing weight and balance calculations, filing and closing FAA flight plans, viewing airport information, and logging flight information in online logbooks.	Cloud
UgCS	Software for planning and flying UAS survey missions, it supports almost any UAV platform, providing convenient tools for areal and linear surveys and enabling direct UAS control.	Desktop Client
Yuneec DataPilot	Complete solution for planning survey and waypoint-based UAS flight. Plan missions offsite and execute missions on-site, allowing for time-planning, collaborative mission planning, and archiving of missions in a cloud or local storage.	Desktop Client
senseFly eMotion	Flights are built using mission blocks. Just choose block (aerial mapping, corridor etc.), highlight the region to map, define key settings, and eMotion auto-generates UAS flight plan. Multi-flight missions are supported and can activate/import elevation data for even safer, terrain-accurate flights.	Desktop Client
SkyVector	Web-based flight planning and filing system.	Cloud

Table 3.6. Commercial off the shelf software applications for UAS flight operations/control.

Application	Description	Computing Model
Skyward	Suite of enterprise software and consulting solutions for safe and effective UAS operations including airspace access (LAANC), flight planning, operational workflow and design, regulatory support, hardware, and APIs	Cloud
DJI Go	Software to control various aspects of flight operations in DJI Enterprise UAS including full control of sensors, take-off and landing, automatic flight logs	Cloud
DJI Pilot	Software to assist DJI Enterprise UAS in real-time picture transmission, flight control, and customized control of sensors.	Cloud
DJI GS Pro	An iPad app for DJI Enterprise UAS for automated flight missions, manage flight data on the cloud, and collaborate across projects to efficiently run the UAS program	Cloud

Application	Description	Computing Model
Litchi	An autonomous flight app for DJI UAS for mission planning, gimbal and sensor control, and automated tracking of objects	Cloud
DroneHarmony	A 3D flight planning software for automated mission planning particularly targeting challenging vertical inspection tasks	Cloud
PX4 AutoPilot	Open source flight control software for UAS operations including mission planning and flight control	Desktop Client
MapPilot	Software for DJI UAS to create optimal flight path and rapidly create high-resolution aerial maps	Cloud
UltimateFlight	An android app for flight control for the DJI Phantom Vision, Phantom Vision+ and the DJI Inspire with next-gen functionalities including Full Ground Station autonomous flights, FPV mode, Phantom track for recording all flight information, home point distance, advanced pre-flight report, and zero altitude offset reporting	Cloud
TopPilot	An application for DJI Phantom and inspire for flight control operations.	Cloud

Table 3.7. Commercial off the shelf software applications for post-UAS flight data processing.

Application	Description	Computing Model
Agisoft Metashape	A stand-alone software that use photogrammetric techniques and computer vision methods to generate 3D Spatial data for GIS applications	Desktop Client
DroneDeploy	A collaborative, cloud-based platform that can be deployed in mobile app; commonly used for UAS mapping to create various photogrammetric outputs and perform aerial site intelligence in real time	Cloud
Skycatch	An enterprise-grade aerial intelligence platform with powerful data analysis tools for data from UAS	Cloud
Propeller	An end-to-end solution that has suite of products to assist ground control and UAS mapping and data analysis of the worksite	Cloud
Trimble Inpho	An Office solution that processes aerial images from UAS using photogrammetry and remote sensing to produce orthomosaics, 3D Surface models, and 3D point clouds	Desktop Client
Bentley ContextCapture	A reality modeling software that uses UAS imagery to produce 3D mesh model of real-world conditions that can be used for design, construction, and operation decisions	Desktop Client
Autodesk Recap	Used for classifying point clouds.	Cloud
Certainty3D TopoDOT	CAD system for extracting features, topography, and 3D models form point cloud data.	Desktop Client
PhotoModeler	Software tool for converting photographs into accurate and useful 3D data and models.	Desktop Client
SimActive Correlator3D	Photogrammetry software with aerial triangulation, DSM and point cloud generation, DTM extraction,	Desktop Client

Application	Description	Computing Model
	orthorectification, mosaic creation, and 3D model generation. Works with any UAS platform and camera/sensor. Additional tools include DEM contour extraction, point cloud colorization, GCP extraction, volume calculation, 3D change detection, and scripting.	
Modri Planet 3D Survey	Photogrammetry software. Ground control point processing. Point classification tools.	Desktop Client
Virtual Surveyor	Used for creating hybrid model from orthomosaics and raster digital elevation models. Also, used for analyzing, cleaning, editing, and exporting data.	Both
Esri Drone2Map	Streamlines the creation of professional imagery products from UAS-captured imagery using a professional photogrammetry suite, powered by Pix4D.	Desktop Client
3DR Site Scan	Process UAS imagery into high-resolution orthomosaics, elevation models, point clouds, 3D meshes, and more with both Pix4D and Autodesk ReCap. Export data into native Autodesk file formats—including RCS and RCM—along with common formats such as OBJ, LAS, and TIFF. Generate detailed processing reports from Pix4D with checkpoints to measure accuracy.	Cloud
Cardinal Systems Vr Mapping VrUAS	Perform Aerial Triangulation, Automatic Point Tie and Bundle Adjustment and to create Digital Surface Models and orthophotos. Also allows for true 3D viewing, vector collection and editing from stereo images and point clouds.	Desktop Client

3.4 Information Technology Infrastructure and Security

IT infrastructure and security for enabling UAS operations are not any more significant than conventional surveying and mapping functions found at many state DOTs. The collection, processing, storage, and management of large volumes of imagery and video data has been a standard industry practice since digital mapping surpassed film-based mapping more than 25 years ago. For those state DOTs that do not have a surveying and mapping function collecting aerial imagery on a regular basis, the transformation may be more significant and warrants discussion.

Regardless of how mature a state DOT is with big data practices, a UAS function should have access to IT resources dedicated to supporting the large volume and velocity of imagery and video data capture including server space and enhanced workstation capability. These resources will allow state DOTs to handle resource-intensive data analytics, deep learning development, and other data science activities to support data-driven decision making. However, the initial investments required may be prohibitive and require a business case to be developed.

3.4.1 Data Governance

Arguably, the most important aspect of a data-driven organization is data governance. State DOTs need to have a data governance framework in place to properly manage all facets of business, geospatial, and source data lifecycle. Faria & Aron (2015) note that risk management, operational efficiency, and value creation are important drivers for effective data governance.

- The risk management objectives include reducing risks, regulation, investigation, and compliance. The primary activities to meet these objectives include compliance, continuity and sustainment, security, and recovery.
- The operational efficiency objectives include cost reduction, transparency, and openness. The primary activities to meet these objectives include information and infrastructure reuse, simplification, automation, and scale.
- The value creation objectives include information value and monetization. The primary activities to meet these objectives include discover, exploration, and experimentation. Depending on the needs of the organization, these drivers will have different levels of influence.

Threlfall (2018) note that many state DOTs are experiencing external influences of advancements and proliferation in transportation technologies such as unmanned aircraft systems, automated and connected vehicles, electronic tolling, and traveler information systems, which adds unexpected strain on government resources. There are also internal pressures to be progressive with integrating the management of programs and driving efficiencies across the organization, which, combined with the pressure to achieve more with fewer resources, is bringing much needed attention to data governance.

Data Management Association International (2017) develops the data management body of knowledge (DMBOK) as a mechanism to convey a standard industry view of data management knowledge, terminology, and best practices. As shown in the DMBOK, data governance encompasses ten key knowledge areas including data architecture, data modeling and design, data storage and operations, data security, data integration and interoperability, documents and content, reference and master data, data warehousing and business intelligence, metadata, and data quality. The importance and priority of each area is driven by priorities of the agency, so public agencies are advised to take a comprehensive approach to structuring a data governance strategy.

UAS data is growing increasingly difficult to manage and process given the large number of images, density of derivative point clouds, large volume of video footage, and shortcomings with data security. Understanding proper data governance protocols for UAS data and other geospatial data is an important consideration for deploying UAS for DOT operations. Large volume geospatial data is not foreign to DOTs, and it is likely DOTs have good data governance for geospatial data. However, recent reports (Mortimer, 2017) suggest that UAS platforms have cyber vulnerabilities. This highlights the need for DOTs to employ good data governance practices including management and security.

There are many reliable and secure solutions available for managing UAS data using cloud computing or on-premise servers. UAS data management should align with agency data governance policies and practices, but there are significant benefits of using a combination of storage solutions. On-premise data storage improves data accessibility and exchange behind the firewall. Sharing data/products that require very limited resources (processors, bandwidth, etc.) is best done through cloud-based platforms. Processing data using cloud solutions is not effective.

3.4.2 Cybersecurity

Cybersecurity has been identified in the FAA UAS integration roadmap as the only required capability that underpins advanced operations (Federal Aviation Administration, 2018). It is vital to the success of all UAS operations, especially those operations around critical infrastructure. DJI was recently found to have transmitted data from UAS operations to China (DJI is based in China), which resulted in many US federal agencies banning their use (Department of Defense in 2017, Department of Interior in 2019, etc.). DJI subsequently worked with the Department of Interior on developing a hardware and firmware upgrade called "Government Edition", which provided a "reasonable mitigation for known data vulnerabilities of the Matrice 600 Pro and Mavic Pro UAS (U.S. Department of the Interior, 2019).

The cybersecurity risk at issue is the data link between the aircraft and the ground control station, which may allow bad actors to passively view video and metadata from the UAS, and even assume control over the UAS. To help mitigate these risks, the Department of Defense recommended not using a removable memory card in the event the UAS is lost; however, it notes that memory on such cards and on the cache of the UAS ground control station can also be wiped before connecting to the internet. Other recommendations include "conducting training in areas that are not operationally sensitive," "cover the camera when not in use" and "do not connect the ground control station to government networks using wired or wireless connections (U.S. Department of the Navy, 2017)."

Implementing the NIST Cybersecurity Framework may enable UAS-specific cybersecurity. This framework consists of five specific functions that can be performed concurrently and continuously to form an operational culture that addresses the dynamic cybersecurity risk. The functions include (National Institute of Standards and Technology, 2014):

- **Identify:** Develop the organizational understanding to manage cybersecurity risk to systems, assets, data, and capabilities.
- **Protect:** Develop and implement the appropriate safeguards to ensure delivery of critical infrastructure services.
- **Detect:** Develop and implement the appropriate activities to identify the occurrence of a cybersecurity event.
- **Respond:** Develop and implement the appropriate activities to take action regarding a detected cybersecurity event.
- **Recover:** Develop and implement the appropriate activities to maintain plans for resilience and to restore any capabilities or services that were impaired due to a cybersecurity event.

The seven-step process for implementing the NIST Cybersecurity Framework for a UAS program includes (National Institute of Standards and Technology, 2014):

1. Prioritizing and scoping UAS business objectives and priorities.
2. Orienting the cybersecurity program with related systems and assets including analysis of threats and vulnerabilities.
3. Developing a current NIST Cybersecurity Framework profile.
4. Conducting a risk assessment.
5. Creating a target NIST Cybersecurity Framework profile.

6. Determining, analyzing and prioritizing gaps between the current and target profiles.
7. Implementing the action plan.

4.0 UAS TECHNOLOGIES TO SUPPORT TRANSPORTATION APPLICATIONS

The selected transportation applications from Task 1 were evaluated to understand the necessary technologies and support systems necessary for integrating UAS technology into traditional workflows. Each transportation application is detailed in subsequent sections, covering compliance requirements and the hardware and software capability of UAS technology that addresses a portion of those requirements. The use of UAS technology does not address all compliance requirements of any selected transportation application. The results of this analysis will showcase application-specific technologies that are necessary to enrich traditional workflows and enhance decision making.

Several industry questionnaires were developed and distributed to various communities to understand what UAS technologies and practices were currently being used for commercial UAS operations (see Appendix A for more information about the questionnaires). These questionnaires informed the UAS technology and support system landscape shown in this chapter.

For reference, Table 4.1 provides a list UAS technologies used by several state DOTs.

Table 4.1. Example list of State DOT UAS technologies

State DOT	UAS Platform	UAS Flight/Data Systems
Alabama DOT	• DJI Phantom 4 • senseFly eBee • senseFly albris	• senseFly eMotion • DJI Go • Pix 4D • Bentley products
Connecticut DOT	• DJI Phantom 4	• DroneLogBook • Bentley products
Maine DOT	• DJI Phantom 4	• DroneLogBook • DJI Go 4 App • DJI Assistant 2 • Bentley products
Massachusetts DOT	• DJI Phantom 4 • DJI Inspire 2 • DJI Matrice 210 • Yuneec H520 • senseFly eBee • Delair UX11	• DroneLogBook • DJI Go 4 App • DJI Assistant 2 • Pix 4D • Autodesk products • Bentley products
Minnesota DOT	• Altus LRX • senseFly albris • Flyability Elios	• Altus Mission Planner • senseFly eMotion • Pix 4D • Trimble Inpho • Esri Drone2Map • Bentley products
Ohio UAS Center	• DJI Phantom 4 Pro RTK	• senseFly eMotion

State DOT	UAS Platform	UAS Flight/Data Systems
	• DJI Inspire 2 • DJI Matrice 210 RTK • DJI Matrice 600 • Flyability Elios • Intel Falcon 8+ • senseFly eBee RTK • Skydio R1	• PostFlight Terra 3D • Pix 4D • Bentley products
Oregon DOT	• DJI Matrice 210 • DJI Phantom 4 • DJI Inspire 2	• DJI Go • Pix 4D • Bentley products
Utah DOT	• senseFly eBee • senseFly albris • WingtraOne • DJI Phantom 4 • DJI Inspire 2 • DJI Matrice 210 • 3DR Solo	• Pix 4D • MapPilot • senseFly eMotion • WingtraHub • Bentley products
Vermont Agency of Transportation	• DJI Phantom 4	• DJI Go 4 App • DJI Assistant 2 • Bentley Products

4.1 General Criteria for Supporting Transportation Applications

The optimal configuration of systems and IT infrastructure necessary to exploit the full value of UAS data should be consistent with other disciplines that collect, processes, manage, and disseminate large volumes of data. Establishing a successful and sustainable UAS program requires certain enterprise elements including safety and quality management systems, additional internet/intranet bandwidth, data storage capacity, on-premises data processing and computing power, cloud computing model framework/policy, data governance protocols, workstation enhancements (processing power, memory, graphics, etc.), and reliable interoperability with discipline-specific decision support systems (e.g. bridge and construction inspection data system(s) of record, asset management systems, emergency response common operating picture systems, etc.).

Each transportation application has unique requirements and criteria for determining the suitability of UAS technology, but for all applications, the following elements should be evaluated (Darby & Gopu, 2018):

- **Technical specifications**: This includes all the physical attributes of the aircraft that impacts the successful operation of an UAS flight for various use cases such as dead weight, waterproof, payload lifting capacity, wind tolerance, flight range, altitude, launch and recovery method, and security features.
- **First Person View**: It is important for the aircraft to provide the PIC first person view so that he/she could see the scenes being shot by the camera/other sensors.

- **Launch and Recovery Mechanisms**: The aircraft should be equipped with sturdy landing gear and/or come with launch and recovery systems. Fixed-wing UAS may require a catapult for launch and space for a belly landing.
- **Payload Attachments**: The UAS should be flexible to accommodate or swap a variety of payloads especially cameras or sensors to collect imageries or information of different types.
- **Gimbal**: The gimbal is an apparatus that attaches to the aircraft and houses the sensor payload. The gimbal can be 2-axis, 3-axis, or gyrostabilized.
- **Camera Shutter type**: The camera should have a stabilizing mechanism to remove vibrations and other noise signals impacting the video and still-photos being collected. It is also desirable to have a camera with global shutter so that it scans the entire area of the image simultaneously.
- **Horizontal and vertical accuracy (HA, VA):** Accuracy of the data being collected is vital to support the needs of UAS operations. As per the ASPRS Positional Accuracy Standards, the horizontal and vertical accuracy represents the component of the positional accuracy of a data set with respect to a horizontal and vertical datum respectively.
- **GSD**: The linear dimension of a sample pixel's footprint on the ground. GSD plays an important role in capturing adequate details of the scan area.
- **Pre-processing and post-processing kits**: The aircraft should come equipped with a compatible flight control software system that can be used to plan and monitor autonomous flights. Preferably, the UAS should also come bundled with a processing software to analyze the collected data and produce necessary outputs to avoid interoperability issues. However, existing Enterprise Licensing Agreements (ELA) with current vendors may provide access to powerful UAS data processing software.

Based on the preferences of New England DOTs identified in Task 1, the research team assigned the following use cases for each New England state DOT for further investigation as shown below in Table 4.2. The supporting technologies for each use case are provided in the subsequent sections.

Table 4.2. New England State DOTs Use cases for investigation

New England State DOT	Use Case
Connecticut DOT	Construction inspection
Maine DOT	Bridge inspection
Massachusetts DOT	Traffic analysis (speed limits and work zones)
New Hampshire DOT	Surveying and mapping for highway design
Rhode Island DOT	Public engagement and outreach
Vermont Agency of Transportation	Emergency response and recovery

4.2 Bridge Inspection (Maine DOT)

The 2007 Keeping Our Bridges Safe (KOBS) report identified enhancing the bridge inventory management as one of the key approaches to strengthen the safety of the bridges in the State of Maine. Periodical inspection of the bridges (and its key elements) per recommended national standards is vital to effectively managing their condition and prioritizing the necessary maintenance and rehabilitation works, given the ageing assets in the state.

Task 1 identified utilizing UAS for bridge inspection as a key area of interest for Maine DOT. This chapter examines the primary data collection requirements to accomplish the objectives of bridge inspection and the ability of an UAS to support these objectives. Specific criteria to be used for selecting a commercially available UAS for bridge inspection are also described. Available products from top manufacturers in the market were compared based on the highlighted criteria.

4.2.1 Types of data

Bridge inspection based on NBIS consists of collecting comprehensive information about the condition of each of the major bridge elements including substructure, superstructure, substructure, and culvert. Element-level inspection has been successfully used across all the States including Maine for data collection, performance assessment, resource allocation, and management decision support. Maine DOT also recommends element level data be collected on all bridges and minor spans during routine inspections that is then used by bridge community to determine bridge needs and priorities. The rating of environmental conditions under which the element is operating is another key requirement of Maine DOT's element-level bridge inspection program.

Deployment of UAS provides opportunities to collect several types of data, as listed below, to support various cases that are of interest to Maine DOT's bridge inspection program and its objectives of collecting element-level data and performing environmental ratings.

- **RGB Imageries:** While inspecting bridge elements as part of routine inspection, high-resolution video and still cameras can be used to produce photographs of elevation, topside, underside, and substructures along with adequate description. The fracture-critical inspection requires inspecting steel members at arm's length and hence it could not be supported uniquely by the use of UAS.
- **Infrared images:** These images are often captured using Forward Looking Infrared Cameras (FLIR), thermal infrared cameras, and multispectral and hyperspectral visible and near-infrared cameras. They are often used to support/augment the information on concrete delamination on bridge decks and other elements.
- **3D models:** Three-models of the bridge and supporting structures can be created by processing the 2D images (through appropriate photogrammetric tool) or by deploying lidar for data collection.
- **Time of Flight Diffraction (TOFD) images:** These images may be used to enhance the information obtained about cracks in concrete.
- **Ultrasonic Images:** Ultrasonic images may be useful provided techniques that can be developed for use with UAS to access bridge concrete structures.

4.2.2 Specific Criteria for UAS selection for bridge inspection

As the use of UAS for bridge inspection matures and the market expands with a variety of UAS manufacturers and service providers supporting UAS operations, it becomes necessary to establish the defining criteria that can help decision-makers select optimal configuration for UAS to suit the objectives of application. Inspection-specific commercial UAS have proven to be cost-effective in collecting detailed visual information and offering other benefits such as improved safety, enhanced onsite productivity, and ability to inspect confined spaces.

Based on reconciling the information from several case studies of UAS applications in transportation projects, the following criteria have been identified. It is also assumed that the UAS should, by default, have a standard multi-copter airframe and should come with a high-resolution video and still photo camera (at-least 12 MP; 38 MP desirable). Other major attributes for evaluation are enlisted below (Darby & Gopu, 2018)

- **Dexterity of manual operation**: The aircraft should have communication systems and capabilities to respond to manual operations from remote location. It should also be possible to manipulate the configuration of sensors through manual operation.
- **Stability**: The aircraft should have stability and sturdiness to withstand potential weather conditions due to rain and wind.
- **External interference**: The aircraft's systems and components should be resistant to potential magnetic interference when deployed for bridge inspection. This issue gains significance especially while deploying UAS for inspecting bridges with steel structures or other ferrous materials. Research suggests that two strongest sources of magnetic interference are the cables connecting the motor to the batteries as well as the servos (used for rotation) (Tasevski, 2018).
- **Confined Spaces**: The aircraft should have support systems to inspect elements of bridges that require scanning over confined spaces to collect required data. This aspect is important for element-level inspections or performing fracture critical inspections.
- **Gimbal**: The UAS camera should have a gimbal for panning up and down and to the extent possible, 360 degrees.
- **Landing Gear**: The aircraft should be equipped with sturdy landing gear and retractable configuration especially if the camera is mounted to the bottom of the aircraft to allow the camera a full 360-degree horizontal pan view.
- **Obstacle Avoidance**: The craft should have the ability to detect obstacles and automatically prevent itself from flying into or being flown into an obstacle to mitigate the possibility of a crash.
- **Flight duration**: The aircraft should have a flight time of at least 20 minutes (desirably around 45 minutes) with a fully charged battery to support autonomous operations.
- **Horizontal and vertical accuracy (HA, VA):** Accuracy of the data being collected is vital to support the needs of UAS operations. As per the ASPRS Positional Accuracy Standards, the horizontal and vertical accuracy represents the component of the positional accuracy of a data set with respect to a horizontal and vertical datum respectively. It is desirable to have a horizontal accuracy of 1.25 cm and a vertical accuracy of 5cm unless there are higher accuracy requirements of a specific aspect of bridge inspection.

4.2.3 Operational requirements for bridge inspection

FAA's Part 107 regulations that govern the use of small UAS provides greater flexibility for commercial operations of the technology for bridge inspection purpose. These rules apply to UAS weighing less than 55lbs, operated within VLOS, using a pilot (who is FAA remote pilot certified) and flown in daylight hours and in the Class "G" airspace. However, routine bridge inspections may require certain deviations to these norms and such deviations must be authorized through waivers. Example include conducting inspection during night times, inspecting bridges/structures that are near airports. In case of Minnesota DOT, a certificate of Authorizations was obtained based on an airspace map (that delineated operational ceilings) thereby obviating the need to obtain waiver for individual bridge sites, producing cost and time effectiveness

4.2.4 Support systems for UAS integration into Bridge Inspection

As described earlier, UAS collects various types of data that convey valuable information regarding the condition of various bridge elements. To effectively archive and use the data collected through UAS, it is essential to have a bridge asset management system that is compatible with the format and scale of the information being collected. Existing state-of-the-art tools such as AASHTOWare Bridge Management Systems®, Bentley AssetWise® includes functionalities for storing, analyzing and updating the inventory and condition data of bridge assets for federal reporting purposes. In practice, images collected through UAS can be used to augment the information being submitted to the bridge management system. Opportunities remain to be explored to integrate other formats of data such as 3D point clouds and 3D models, in raw or other formats, for various purposes (such as forecasting determination, life-cycle cost assessment, determination of work programs and implementation schedules, and maintaining a digital model of the facility with latest inventory information).

Recent advancements in artificial intelligence (including machine learning and deep learning) practices and technologies can be effectively used for traffic analysis. Deep learning can be used to automatically extract deep insights from UAS imagery and video in near real-time. A deep learning technology stack includes deployment/computer vision toolkits, frameworks (Apache Spark, Theano, torch, etc.), libraries (Intel DAAL/MKL/MLSL, etc.), and computational hardware (processors, memory and storage, networking, and visual intelligence). A deep learning support system includes partnering with IT authorities to ensure compliance and effective implementations. In more advanced UAS operations, a deep learning technology stack can automate defect recognition.

In terms of hardware and platform capabilities, an internet search was conducted to identify available UAS manufacturers that had largest market share servicing transportation industry and developing UAS that would comply with the operational requirements and data needs identified for bridge inspection. Following list of UAS are compared.

- senseFly albris UAS
- Intel Falcon 8+ (with Sony Alpha 7R)
- Flyability Elios UAS*
- DJI Mavic Pro
- DJI Inspire 2 (with Zenmuse X7)
- DJI M200 Series V2 (with Zenmuse X7)

Table 4.3 compares the UAS mentioned above based on the evaluation criteria identified for deploying UAS for bridge inspection. While the information is based on best available information from product sheets and specifications currently available, it is to be noted that product upgrades continue to happen in the market. As such, it is recommended to contact the concerned manufacturers regarding the latest specifications of the UAS systems while making procurement decisions.

Table 4.3. Comparison of UAS characteristics for selected UAS products for bridge inspection

Characteristics	SenseFly albris UAS	Flyability Elios 2	DJI Mavic 2 Pro	DJI Inspire 2	DJI M210 Series V2/RTK	Intel Falcon 8+
Type	V-shaped quadcopter	Collision-tolerant Quadcopter	Quadcopter	Quadcopter	Quadcopter	Octocopter
Weight	NA	NA	NA	3.44 kg (7.58 lbs.)	4.69 kg	1.2 kg (2.65 lbs.)
Payload + Weight	1.8 kg (3.9LBS)	0.7 kg	0.907 kg	4.25 kg (9.37 lbs.)	6.14 kg	2.0 kg (4.4 lbs.)
Wind resistance	8-10 mph	~11 mph	18 - 23 mph	23 mph	27 MPH	27 mph
Ingress Protection	NA	NA	NA	NA	IP43	NA
Range	0.5 miles to 1.2 miles	Up to 500m	Typically, 5-10 km	Up to 7KM	NA	up to 1km
Altitude	NA	NA	NA	NA	NA	4000 m (13,123 ft)
Operating temperature	-10 to 40 deg Celsius	0 to 50 deg Celsius	0 to 40 deg Celsius	-20 to 40 deg Celsius	-20 to 50 deg Celsius	-5 to 40 deg Celsius
Launching/ Landing Mechanism	None	None	None	None	None	None
Payload - Images/FOV	38MP / 63 degrees H	130 degrees H and 75 degrees V	5247 X 3648	24MP / 300 degrees H and 180 degrees V	24MP / 300 degrees H and 180 degrees V	36MP
Payload – Videos	HD (1280 x 720)	HD (1920x 1080)	3840 x 2160	6016 x 3200 (ProRes)	6016 x 3200 (ProRes)	HD (1920x 1080)
Payload – Thermal/FOV	80 x 60 /50 H	160 x 120/56H/42 V	NA	Swappable	Swappable	NA
Payload – SAR/Others	NA	NA	NA	Swappable	Swappable	Near-Infrared camera
Payload – Gimbal	Yes, not 360 deg	Yes, not 360 deg	Yes, not 360 deg	Yes	Yes, not 360 deg	Yes, not 360 deg
Payload – Camera Shutter	NA	NA	Electronic	NA	Electronic and Mechanical	NA
Ground Control Points	Yes	Yes	Yes	Yes	No, RTK enabled	Yes
HA/VA	NA	NA	NA	NA	NA	NA
GSD	1 cm/pixel at 60m	0.2mm/pixel	NA	Varies	Varies	NA
Flight duration	22 min	10 min max.	31 mins	25 mins	24 mins	16-26 mins
Obstacle Avoidance	Yes (Ultrasonic)	Yes	Yes	Yes	Yes	Yes

Characteristics	SenseFly albris UAS	Flyability Elios 2	DJI Mavic 2 Pro	DJI Inspire 2	DJI M210 Series V2/RTK	Intel Falcon 8+
Pre-processing /Flight planning, controls	eMotion	Yes	DJI Terra, FlightHub, GS Pro	DJI Terra, FlightHub, GS Pro	DJI Terra, FlightHub, GS Pro	Yes
Post-processing/Data Analysis	Pix4D	Yes	DJI Terra, FlightHub, GS Pro	DJI Terra, FlightHub, GS Pro	DJI Terra, FlightHub, GS Pro	NA
Price*	~$ 6,000	~$1,000 - $5,000	$1,729	$3,499	$6,000+	$16,359
Link	https://www.sensefly.com/app/uploads/2018/05/albris_EN.pdf	https://www.flyability.com/elios-2	https://www.dji.com/mavic-2/info#specs	https://www.dji.com/inspire-2/info#specs	https://www.dji.com/matrice-200-series-v2/info#specs	https://www.intel.com/content/www/us/en/drones/falcon-8-plus-brochure.html

*Quoted price is an estimate. Please contact the manufacturer to request a formal quote
NA - Not Available/Apparent; GCP – Ground Control Points Required; HA – Horizontal Accuracy; VA – Vertical Accuracy; GSD – Ground Sample Distance

4.3 Construction Inspection (Connecticut DOT)

The Connecticut Department of Transportation had identified maintenance of its assets in State of Good Repair as its highest priority in its Strategic Five-Point Action Plan to address systemic challenges followed by enhancing safety and increased modernization of assets. The Agency's Asset Management Plan also pivots the need of emerging technologies to incorporate the necessary changes in business practices to support key transportation applications. Technology assisted inspection during construction phase can improve the overall efficiency, agility, and accuracy of various tasks such as quality control checks, safety monitoring, and quantity estimation process.

Task 1 identified utilizing UAS for construction inspection as one of the areas of for Connecticut DOT. This chapter examines the primary data collection requirements to accomplish the objectives of construction inspection and the ability of the UAS to support these objectives. Specific criteria to be used for selecting a commercially available UAS for construction inspection are also described. Available products from top manufacturers in the market were compared based on the highlighted criteria.

4.3.1 Types of data

Performing construction inspection requires collecting various types of data to support verification, acceptance, and inspection of key construction elements of a transportation project. The inspection requirements for various elements have been enumerated as checklists in the agency website (https://portal.ct.gov/DOT/Office-of-Construction/Pocket-Guide-Checklists) and the scope covers drilled shaft, drainage, excavations, work zones, concrete, cofferdam, pavement, and steel construction among others. It is also reported that CTDOT is updating inspection manuals to incorporate new workflows to use digital data for real-time verification and quantity measurement. Digital tools such as UAS help in collecting a variety of data in synchronization with other construction technologies such as GNSS rovers, AMG, infrared sensors., for inspection purposes supporting a variety of objectives.

Deployment of UAS provides opportunities to collect several types of data, as listed below, to support various cases that are of interest CTDOT's construction inspection program.

- **RGB Imageries:** RGB imageries of construction jobsites and construction elements can be used to monitor construction progress and identify safety hazards. High resolution imageries of grading, excavation, linear-pay items, and stockpiles can often be used to ascertain or verify quantities or compare the quantities obtained using traditional estimation methods.
- **3D Models**: UAS fitted with laser scanners can produce digital point cloud models that can be used for several inspection tasks including quality control checks, quantity estimation, as-built documentation. Such point cloud data can be processed through pertinent object recognition and segmentation software to produce detailed 3D models of roadway surface (DSM), structures, and other assets.
- **Infrared images**: Although not commonly used for inspection purposes, images obtained through FLIR sensors or equivalent fitted in an UAS can provide contact-free temperature assessment of various elements on construction jobsites.
- **Radar data:** Although rare, UAS can be fitted with Synthetic Aperture Radar (SAR) payload to support construction site mentoring applications especially in areas that has adverse lighting or weather conditions prohibiting visualization of construction items.

4.3.2 Specific Criteria for UAS selection for construction inspection

As the use of UAS expands for construction inspection and the capabilities of the technological solution expands with new service providers and manufacturers, it becomes necessary to establish objective criteria for construction inspection. Inspection-specific commercial UAS have proven to be cost-effective in collecting detailed visual information and offering other benefits such as improved safety, enhanced onsite monitoring, accurate estimate of quantities, and ability to inspect construction in confined spaces.

The criteria identified below for construction inspection aligns considerably with that of the ones identified for bridge inspection. It is also assumed that the UAS should, by default, have a standard multi-copter airframe and should come with a high-resolution video and still photo camera (at-least 12 MP; 38 MP desirable). Other major attributes for evaluation are enlisted below.

- **Platform type:** UAS platform type assumes significance for construction inspection. For narrow roadway corridors with considerable wind speeds, VTOL configuration is preferable although it has lower battery life. However, fixed-wing aircraft can be conveniently deployed if the jobsite is considerably large with large area available to facilitate take-off and landing.
- **Ground Sample Distance (GSD)**: The linear dimension of a sample pixel's footprint on the ground. GSD is important to capture adequate details for construction (specifically for quantity estimation) and its current state to support inspection needs. A GSD of around 5 cm is preferred.
- **Flight duration**: The aircraft should have a flight time of at least 20 minutes (desirably around 45 minutes) with a fully charged battery to support autonomous operations. Longer duration is usually preferred for active construction site monitoring (30+ mins), while shorter duration (of

around 20-25 mins) would suffice for collecting point cloud data for estimating or verifying quantities.

- **Pre-processing and post-processing kits**: The aircraft should come equipped with a compatible flight control software system that can be used to plan and monitor autonomous flights. Preferably, the UAS should also come bundled with a processing software to analyze the collected data and produce necessary outputs for construction inspection. This would include photogrammetric solutions and 3D point cloud processing tools for volumetric assessment.

4.3.3 Operational requirements for construction inspection

FAA's Part 107 regulations that govern the use of small UAS provides greater flexibility for commercial operations of the technology for bridge inspection purpose. These rules apply to UAS weighing less than 55lbs, operated within VLOS, using a pilot (who is FAA remote pilot certified) and flown in daylight hours and in the Class "G" airspace. On a few occasions, construction inspection may require certain deviations to these norms and such deviations must be authorized through waivers. Example include monitoring construction jobsites during night times, deploying UAS for construction inspection on sites that are near airports. With the evolution of the LAANC (Low Altitude Authorization and Notification Capability) system the FAA response time has been greatly curtailed allowing the flight operators to comply with the regulations easily.

4.3.4 Support systems for UAS integration into Construction Inspection

UAS have been identified as one of the enabling technologies towards digitalization of construction inspection processes. High-resolution orthomosaics and volumetric data gained through analysis of point clouds can be successfully utilized for real-time verification and quantity measurements for lump-sum pay items, daily construction monitoring, and materials sampling. Supporting information systems such as SiteManager, AASHTOWare Project Construction and Materials Software play a vital role in utilizing and documenting the electronic information for construction inspection. Equally important to the information systems are communication networks that sufficiently integrates office and field environments. the ability to use mobile location-aware devices, such as a wireless local area network (WLAN) and Bluetooth Low Energy technology, for real-time tracking of feature locations in GNSS signal-deficient areas, such as in buildings, urban canyons, and underground is important to ensure real-time verification/QC of the worker's device on the field. Information once collected can be transferred using Virtual Private Networks (VPN) or stored in flash drive to be transmitted and synced later to the network (Mitchell, Gustafson, Gensib, & Maier, n.d.).

In terms of hardware and platform capabilities, an internet search was conducted to identify available manufacturers that had largest market share servicing transportation industry and developing UAS that would comply with the operational requirements and data needs identified for construction inspection. Following list of UAS are compared.

- Trimble UX5
- Skycatch Explore 1 RTK
- SenseFly eBee X
- DJI M210 Series 2

- DJI Phantom 4 RTK

Table 4.4 compares the UAS mentioned above based on the evaluation criteria identified for deploying UAS for construction inspection. While the information is based on best available information from product sheets and specifications currently available, it is to be noted that product upgrades continue to happen in the market. As such, it is recommended to contact the concerned manufacturers regarding the latest specifications of the UAS systems while making procurement decisions.

Table 4.4. Comparison of UAS characteristics for selected UAS products for construction inspection

Characteristics	Trimble UX5 HP	Skycatch Explore 1 RTK	SenseFly eBee X	DJI M210 Series V2/RTK	DJI Phantom 4 RTK
Type	Fixed Wing	Quadcopter VTOL	Fixed Wing	Quadcopter	Quadcopter
Weight	2.9 kg (6.4 lbs.)	NA	NA	4.69 kg	NA
Payload + Weight	NA	3.6 kg	1.4 kg (3.1 lbs.)	6.14 kg	1.39 kg
Wind resistance	Up to 34 mph	NA	Up to 29 mph	27 mph	NA
Ingress Protection	NA	NA	NA	IP43	NA
Range	Up to 32 miles (communication range up to 3.1 miles)	Communication range up to 3.1 miles)	Up to 30 miles (communication range up to 3.1 miles)	NA	NA
Altitude	75m to 750m AGL	NA	NA	NA	NA
Operating temperature	NA	10 to 40 deg Celsius	-10 to 40 deg Celsius	-20 to 50 deg Celsius	0 to 40 deg Celsius
Launching/ Landing Mechanism	Catapult/Belly Landing	None	Hand Launch/Belly Landing	None	None
Payload - Images/FOV	36MP	16 MP	Multiple SenseFly Cameras	24MP (Zenmuse X7)	20MP
Payload - Videos	NA	NA	NA	6016 x 3200 (ProRes)	3840 x 2160 3p
Payload - Thermal/FOV	NA	NA	NA	Swappable	NA
Payload - SAR/Others	NA	NA	NA	Swappable	Yes
Payload - Gimbal	No	No	No	Yes, not 360 deg	Yes, not 360 deg
Payload - Camera Shutter	NA	Mechanical	Global	Electronic and Mechanical	Mechanical
GCP	No, PPK enabled	No, PPK enabled	No, with included High-Precision on Demand (RTK/PPK)	No, RTK enabled	No, RTK enabled

Characteristics	Trimble UX5 HP	Skycatch Explore 1 RTK	SenseFly eBee X	DJI M210 Series V2/RTK	DJI Phantom 4 RTK
HA/VA	2-5cm	Up to 3cm/ Up to 5cm	Up to 3cm	NA	NA
GSD	around 2cm (1-25cm)	1cm	2.5 cm/px (1.0 in/px) at 400FT	Varies	6.5cm/px
Flight Duration	40 mins	20 mins	Up to 90 mins	24 mins	Up to 30 mins
Obstacle Avoidance	No	No	No	yes	yes
Pre-processing /Flight planning, controls	Trimble Access Aerial Imaging Application	Skycatch Flight Plan System (Tablet)	eMotion	DJI Terra, FlightHub, GS Pro	DJI Terra, FlightHub, GS Pro
Post-processing/Data Analysis	Trimble UASMaster, Business Center	Agisoft	Pix4D, Agisoft, Trimble Business Center	DJI Terra, FlightHub, GS Pro	DJI Terra, FlightHub, GS Pro
Price*	~25,000	NA	~20,000	$6,000+	$6,000+
Link	http://www.kmcgeo.com/Datasheets/UX5HP.pdf	http://explore1.skycatch.com/	https://www.senseFly.com/app/uploads/2018/09/eBee-X-EN.pdf	https://www.dji.com/matrice-200-series-v2/info#specs	https://www.dji.com/phantom-4-rtk/info#specs

*Quoted price is an estimate. Please contact the manufacturer to request a formal quote
NA - Not Available/Apparent; GCP – Ground Control Points Required; HA – Horizontal Accuracy; VA – Vertical Accuracy; GSD – Ground Sample Distance

4.4 Traffic Analysis (Massachusetts DOT)

The interests of MassDOT to explore UAS for traffic analysis strategically aligns with its mission to enhance the customer experience by providing enhanced safety and reliability on its highways. The agency supports programs and investments that yield a high investment to achieve its stated missions. UAS can be deployed for monitoring traffic conditions and collect real time data for traffic analyses. They have been found to be effective in monitoring traffic in intersections and smaller areas within the range of sensor payload. They can be successfully used for short term traffic studies and work zone safety assessment. However, collecting traffic data over larger region using UAS might have limitations due to battery and VLOS requirements.

Task 1 identified utilizing UAS for traffic analysis as one of the areas of for Massachusetts DOT. This chapter examines the primary data collection requirements to accomplish the objectives of traffic analysis, specifically focusing on speed limit assessment and work zone safety. Specific criteria to be used for selecting a commercially available UAS for traffic analysis are also described. Available products from top manufacturers in the market were compared based on the highlighted criteria.

4.4.1 Types of data

UAS can be a flexible tool to collect real-time traffic data that can be utilized to support various analysis and congestion management measures. It can also provide valuable information benefitting commuters enhancing the overall mobility and safety of the corridor. Instances exist in the literature where UAS had been successfully used to collect a wide range of traffic data including speed, flow rates, travel time, and vehicle types among others. Usage of UAS also provides the capability to live-stream videos to traffic operation centers in real time. UAS data can be also used to verify and augment the information collected by other sensor technologies such as loop detectors and radar sensors, and enhance the performance of various active traffic management technologies such as ramp metering, reversible lanes, variable speed limits etc. Monitoring construction work zones using UAS can also provide vital information about the project (including its progress, quantity estimates) and enhances the safety of the customers.

Deployment of UAS for traffic analysis provides opportunities to collect several types of data, as listed below, to support various cases that are of interest to MassDOT.

- **RGB Imageries and videos:** RGB imageries and live videos collected from UAS can be successfully processed to extract useful traffic information such as traffic counts, speed, vehicle classification, level of service, and origin-destination flows. Such data can be effectively used for traffic management and emergency identification and response.
- **3D Models**: UAS fitted with laser scanners can produce digital point cloud models that can be used to rapidly analyze the status of construction work zones on highways and identify potential safety hazards besides other common applications including construction progress monitoring, quality control checks and quantity estimation. Such point cloud data can be processed through pertinent object recognition and segmentation software to produce detailed 3D models of roadway surface (DSM), structures, and other assets.
- **Radar data:** Although not commonly used for traffic analysis purposes with UAS platform, radar sensors can be used to collect travel speed information of vehicles on highways.

4.4.2 Criteria for UAS selection for traffic analysis

The use of UAS for collecting traffic data and incident management has been on the consistent rise over the past few years. Inspection-specific commercial UAS have proven to be cost-effective in collecting detailed visual information and offering other benefits such as improved safety during data collection and ability to measure key traffic metrics to assist traffic flow monitoring, congestion management, and incident response.

The criteria identified below for traffic analysis aligns well with the necessary objectives for the mission especially collecting detailed, real-time information about traffic flow such as speed, volume, counts and provide the decision-makers to respond swiftly to changing traffic conditions and incidents. It is also assumed that the UAS should, by default, have a standard multi-copter airframe and should come with a high-resolution video and still photo camera (at-least 12 MP; 38 MP desirable). Other major attributes for evaluation are enlisted below.

- **Platform type:** Deploying UAS for traffic analysis would necessitate using different kind of platforms depending on the specific objectives of the mission. Untethered VTOL aircrafts can be used if monitoring smaller intersections over shorter period, whereas tethered UAS platforms can be used for extended flight time and surveillance requiring live data transfer to ground stations. A tethered platform may require additional accessories including generators and power controllers.

- **Ground Sample Distance (GSD)**: The linear dimension of a sample pixel's footprint on the ground. GSD is important to capture adequate details for traffic monitoring and transfer the information for appropriate congestion management and response strategies. A GSD of around 5 cm is preferred.
- **Flight duration**: The aircraft should have sufficient flight time to complete the objectives of the mission. A minimum duration of 30 minutes is preferred for short-term data collection or response, while a tethered platform with infinite flight time can be used for permanent traffic surveillance and traffic data collection efforts.
- **Obstacle Avoidance**: The craft should can detect obstacles and automatically prevent itself from flying into or being flown into an obstacle (especially commuters, highway assets) to mitigate the possibility of a crash.
- **Pre-processing and post-processing kits**: The aircraft should come equipped with a compatible flight control software system that can be used to plan and monitor autonomous flights. In case of tethered platforms, any additional set up for power control and communication software should also be considered Preferably, the UAS should also come bundled with a processing software to analyze the collected data and produce necessary outputs for traffic analysis. This would include high-resolution imageries, video streams, and 3D scene mapping.

4.4.3 Operational requirements for traffic analysis

FAA's Part 107 regulations that govern the use of small UAS provides greater flexibility for commercial operations of the technology for traffic operations. These rules apply to UAS weighing less than 55lbs, operated within VLOS, using a pilot (who is FAA remote pilot certified) and flown in daylight hours and in the Class "G" airspace. On a few occasions, monitoring traffic operations may require using UAS beyond VLOS. Example include launching UAS to monitor large section of an active freeway, monitoring space-constrained traffic segments or deploying UAS near airports. With the evolution of the LAANC (Low Altitude Authorization and Notification Capability) system the FAA response time has been greatly curtailed allowing the flight operators to comply with the regulations easily. State Laws must be examined to ensure compliance on limitations of using the image/video data being gathered using UAS for traffic monitoring. The ability of a service provider to fly over public right of way need to be considered and clarified as per the State Law (Stevens Jr. & Blackstock, 2017).

4.4.4 Support systems for UAS integration into traffic analysis

UAS provides live-video feeds and other forms of information that assist in significantly in analyzing various parameters of traffic flow. Operators at traffic management centers normally use several Active Traffic Management Software (ATMS) systems (such as SunGuide, LoneStar) to monitor traffic conditions and make key decisions to respond to any incidents. Several ITS devices (such as CCTVs, DMS, radar sensors) are integrated into the ATMS to collect and analyze traffic data and use them for traffic monitoring and decision-making. It is quite possible to integrate UAS data to support understanding of traffic conditions being predicted by other devices. With the advent of connected vehicles expected soon, agencies are investing on setting up Dedicated Short-Range Communication (DSRC) devices capable of Signal Phases and Timing (SPaT) broadcasts that relays the current state of intersections. The sensors on UAS could be used to support defining the SPaT messages or add additional information improving the reliability and accuracy of the information being conveyed (National Operations Center of Excellence, 2019).

Recent advancements in artificial intelligence (including machine learning and deep learning) practices and technologies can be effectively used for traffic analysis. Deep learning can be used to automatically extract deep insights from UAS imagery and video in near real-time. A deep learning technology stack includes deployment/computer vision toolkits, frameworks (Apache Spark, Theano, torch, etc.), libraries (Intel DAAL/MKL/MLSL, etc.), and computational hardware (processors, memory and storage, networking, and visual intelligence). A deep learning support system includes partnering with IT authorities to ensure compliance and effective implementations. In more advanced UAS operations, a deep learning technology stack can automate feature recognition for speed limit studies and work zone management.

With regards to hardware and platform capabilities, an internet search was conducted to identify available manufacturers that had largest market share servicing transportation industry and developing UAS that would comply with the operational requirements and data needs identified for traffic analysis. Following list of UAS are compared.

- DJI Inspire 2
- FLIR/Aria PARC tethered UAS
- SenseFly eBee X
- DJI M200 Series V2
- Hoverfly LiveSky SENTRY

Table 4.8 compares the UAS mentioned above based on the evaluation criteria identified for deploying UAS for traffic analysis. While the information is based on best available information from product sheets and specifications currently available, it is to be noted that product upgrades continue to happen in the market. As such, it is recommended to contact the concerned manufacturers regarding the latest specifications of the UAS systems while making procurement decisions.

Table 4.5. Comparison of UAS characteristics for selected UAS products for traffic analysis

Characteristics	LiveSky Sentry	FLIR/Aria PARC Tethered	SenseFly eBee X	DJI Inspire 2	DJI M210 Series V2/RTK
Type	Hexacopter	Quadcopter	Fixed Wing	Quadcopter	Quadcopter
Weight	2.3kg (5 lbs.)	NA	NA	3.44 kg (7.58 lbs.)	4.69 kg
Payload + Weight	NA	6 lbs.	1.4 kg (3.1 lbs.)	4.25 kg (9.37 lbs.)	6.14 kg
Wind Resistance	Yes	Yes	Up to 29 mph	23 mph	27 MPH
Ingress Protection	Yes	Yes	NA	NA	IP43
Range	NA	NA	Up to 30 miles (communication range up to 3.1 miles)	Up to 7KM	NA
Altitude	60m	122m	NA	NA	NA

Characteristics	LiveSky Sentry	FLIR/Aria PARC Tethered	SenseFly eBee X	DJI Inspire 2	DJI M210 Series V2/RTK
Operating temperature	20 to 55 deg C	-20 to 45 deg C	-10 to 40 deg Celsius	-20 to 40 deg Celsius	-20 to 50 deg Celsius
Launching/ Landing Mechanism	Nest/Nest	None/None	Hand Launch/Belly Landing	None	None
Payload - Images/FOV	Custom	EO Zoom Camera	Multiple SenseFly Cameras	24MP / 300 degrees H and 180 degrees V	24MP / 300 degrees H and 180 degrees V
Payload - Videos	Visible EO HD	Long Range Zoom EO	NA	6016 x 3200 (ProRes)	6016 x 3200 (ProRes)
Payload - Thermal/FOV	Dual IO/ER	Long Range Zoom EO/IR	NA	Swappable	Swappable
Payload - SAR/Others	MPU5 MANET radio	Mobile Ad Hoc Networks, 4G LTE, RADAR	NA	Swappable	Swappable
Payload - Gimbal	Yes	Yes	No	Yes	Yes, not 360 deg
Payload - Camera Shutter	Custom	Custom	Global	NA	Electronic and Mechanical
GCP	Custom	Custom	No, with included High-Precision on Demand (RTK/PPK)	Yes	No, RTK enabled
HA/VA	Custom	Custom	Up to 3cm	NA	NA
GSD	NA	NA	2.5 cm/px (1.0 in/px) at 400FT	Varies	Varies
Flight duration	Unlimited	Unlimited	Up to 90 mins	25 mins	24 mins
Obstacle Avoidance	Yes	Yes	No	Yes	Yes
Pre-processing/ Flight planning/ controls	Hoverfly SDK		eMotion	DJI Terra, FlightHub, GS Pro	DJI Terra, FlightHub, GS Pro
Post-processing/ Data Analysis			Pix4D, Agisoft, Trimble Business Center	DJI Terra, FlightHub, GS Pro	DJI Terra, FlightHub, GS Pro
Price*	Contact Vendor	Contact Vendor	~20,000	$3,499	$6,000+

Characteristics	LiveSky Sentry	FLIR/Aria PARC Tethered	SenseFly eBee X	DJI Inspire 2	DJI M210 Series V2/RTK
Link	https://cdn.newswire.com/files/x/49/58/ca4aa4532b0613c7bad64ae11977.pdf	https://www.ariainsights.com/wp-content/uploads/2019/01/AriaInsights_PARC_Specs_1901.pdf	https://www.sensefly.com/app/uploads/2018/09/eBee-X-EN.pdf	https://www.dji.com/inspire-2/info#specs	https://www.dji.com/matrice-200-series-v2/info#specs

*Quoted price is an estimate. Please contact the manufacturer to request a formal quote
NA - Not Available/Apparent; GCP – Ground Control Points Required; HA – Horizontal Accuracy; VA – Vertical Accuracy; GSD – Ground Sample Distance

4.5 Surveying and Mapping for Highway Design (New Hampshire DOT)

UAS equipped with RGB cameras and light detection and ranging (lidar) sensors are becoming more commonly deployed for the data collection for surveying and mapping. UAS platforms are quick to deploy and offer a much more cost-effective approach to conducting topographic surveys than airborne photogrammetry and terrestrial laser scanning systems. UAS application in surveying and mapping for highway design can be generalized into two methods; UAS lidar and UAS photogrammetry. Both approaches use different sensors to capture topographic data, but the sensor system can be mounted on any UAS that can safely carry to payload.

Surveying and mapping activities are typically governed by state law in order to protect the health, safety, and welfare of the public. As such, professional oversight is typically required to ensure the data being used is of sufficient quality and integrity to support engineering design. In order to verify data quality and integrity as well as validate the data set against requirements, the responsible-charge professional requires transparency and control over the UAS flight and data parameters. Many cloud-based UAS data processing services provide “blackbox” solutions that generate UAS data products automatically without the necessary controls. In general, this is insufficient and potentially unethical for lawful surveying and mapping activities.

4.5.1 UAS Photogrammetry

Aerial photogrammetry with industrial grade ultra-high resolution camera on a fixed wing manned aircraft has been the primary way of aerial mapping in the last century. This mapping technique has evolved rapidly in the past decade and now it has become greatly autotomized making it easily accessible to users. While fundamental mathematics of photogrammetry is essentially the same in the modern computer vision photogrammetry, but the cumbersome process of aero-triangulation and data extraction is being replaced by the software.

4.5.2 UAS Lidar

Lidar is a remote sensing technology where the environment is scanned with a pulsed laser beam and the reflection time of the signal from the object back to the detector is measured. During the scanning process, the lidar system will gather individual distance points within an aggregate of points, from which

3D images of the environment can be computed. The laser scanners deflect the laser beam using deflecting mirrors, which enable them to achieve very wide field of view (FOV).

Most of the latest UAS lidar systems can rotate around their own axis and offer 360-degree visibility. Modern devices achieve very high data rates with over one million distance points per second.

4.5.3 Specific Criteria for UAS selection for Surveying and Mapping for Highway Design

Based on reconciling the information from several case studies of UAS applications in transportation projects, the following criteria have been identified. It is also assumed that the UAS should, by default, have a standard multi-copter airframe and should come with a high-resolution video and still photo camera (at-least 12 MP; 38 MP desirable). Other major attributes for evaluation are enlisted below.

- **Technical specifications:** This includes all the physical attributes of the aircraft that impacts the successful operation of an UAS flight for bridge inspection such as dead weight, waterproof, payload lifting capacity, wind tolerance, BLOS range, Altitude, launch and recovery method, and security features.
- **First Person View:** It is important for the aircraft to provide the PIC first person view so that he/she could see the scenes being shot by the camera/other sensors.
- **Landing Gear:** The aircraft should be equipped with sturdy landing gear and retractable configuration especially if the camera is mounted to the bottom of the aircraft to allow the camera a full 360-degree horizontal pan view
- **Payload Attachments**: The UAS should be flexible to accommodate or swap a variety of payloads especially cameras or sensors to collect imageries or information of different types
- **Gimbal:** The UAS camera should have a gimbal for panning up and down and to the extent possible, 360 degrees.
- **Flight duration:** The aircraft should have a flight time of at least 20 minutes (desirably around 45 minutes) with a fully charged battery to support autonomous operations
- **Obstacle Avoidance**: The craft should have the ability to detect obstacles and automatically prevent itself from flying into or being flown into an obstacle to mitigate the possibility of a crash.

4.5.4 Operational requirements for surveying and mapping for highway design

4.5.4.1 Pre-processing and post-processing kits

The aircraft should come equipped with a compatible flight control software system that can be used to plan and monitor autonomous flights. Preferably, the UAS should also come bundled with a processing software to analyze the collected data and produce necessary outputs necessary for the project’s design.

UAS operate internally on proprietary firmware but can usually be either controlled remotely by a pilot or preprogrammed with a set flight path. Data can be captured manually or at set intervals using proprietary or third-party software. Most of the branded UAS can be operated using a mobile device through applications that operate on both the Apple iOS and Android platforms.

4.5.4.2 Flight Control Software

Most UAS come equipped with their own branded control applications, but many third-party applications that operate as effectively as the branded software can be installed depending on flight requirements or user preferences. This third-party software can be a substitute for either the existing remote flight control or autonomous flight planning and control software.

4.5.5 Support systems for UAS integration into surveying and mapping

Using UAS for highway design requires professional oversight and robust control systems to ensure suitability and sufficiency. The primary support system for verifying and validating UAS data for highway design requires all UAS flight planning, control, and processing to be conducted under a state-licensed professional surveyor/mapper or ASPRS certified photogrammetrist, whichever is required by state law. This responsible-charge professional will provide supervision and direction of all activities under their purview and ensure lawful practice through their professional judgment.

In terms of hardware and platform capabilities, an internet search was conducted to identify available UAS manufacturers that had largest market share servicing transportation industry and developing UAS that would comply with the operational requirements and data needs identified for surveying and mapping. Following list of UAS are compared.

- DJI Phantom 4 (with 4 PRO Series Camera)
- DJI M6OO PRO (with Phase one Ixm 100 camera)
- Intel Falcon 8+ (with Sony Alpha 7R)
- SenseFly eBee X

Table 4.7 below compares the UAS mentioned above based on the evaluation criteria identified for deploying UAS for surveying and mapping. While the information is based on best available information from product sheets and specifications currently available, it is to be noted that product upgrades continue to happen in the market. As such, it is recommended to contact the concerned manufacturers regarding the latest specifications of the UAS systems while making procurement decisions.

Table 4.6. Comparison of UAS characteristics for selected UAS products for surveying and mapping

Characteristics	DJI M600 Pro	SenseFly eBee X	DJI Phantom 4 RTK	Intel Falcon 8+
Type	Hexacopter	Fixed Wing	Quadcopter	Octocopter
Weight	9.5 kg	NA	NA	1.2 kg (2.65 lbs.)
Payload + Weight	15.5 kg	1.4 kg (3.1 lbs.)	1.39 kg	2.0 kg (4.4 lbs.)
Wind resistance	18	Up to 29mph	NA	27 mph
Ingress Protection	NA	NA	NA	NA
Range	Typically, 3.1 miles (5 km)	Up to 30 miles (communication range up to 3.1 miles)	NA	up to 1km
Altitude	NA	NA	NA	4000 m (13,123 ft)
Operating temperature	-10 to 40 deg C	-10 to 40 deg C	0 to 40 deg Celsius	-5 to 40 deg Celsius

Characteristics	DJI M600 Pro	SenseFly eBee X	DJI Phantom 4 RTK	Intel Falcon 8+
Launching/ Landing Mechanism	None	Hand Launch/Belly Landing	None	None
Payload - Images/FOV	100 MP (Phase one Ixm) Various (DJI Zenmuse Z and X series)	Multiple SenseFly Cameras	20MP	36MP
Payload – Videos	Various (DJI Zenmuse Z and X series)	NA	3840 x 2160 3p	HD (1920x 1080)
Payload – Thermal/FOV	NA	NA	NA	NA
Payload – SAR/Others	NA	NA	Yes	Near-Infrared camera
Payload – Gimbal	Yes, not 360 deg	No	Yes, not 360 deg	Yes, not 360 deg
Payload – Camera Shutter	NA	Global	Mechanical	NA
Ground Control Points	Yes	No, with included High-Precision on Demand (RTK/PPK)	No, RTK enabled	Yes
HA/VA	NA	Up to 3cm	NA	NA
GSD	NA	2.5 cm/px (1.0 in/px) at 400FT	6.5cm/px	NA
Flight duration	16-18 mins (32 mins without payload)	Up to 90 mins	Up to 30 mins	16-26 mins
Obstacle Avoidance	Yes	No	yes	Yes
Pre-processing /Flight planning, controls	DJI Terra, FlightHub, GS Pro	eMotion	DJI Terra, FlightHub, GS Pro	Yes
Post-processing/Data Analysis	DJI Terra, FlightHub, GS Pro	Pix4D, Agisoft, Trimble Business Center	DJI Terra, FlightHub, GS Pro	NA
Price*	$6,000+	~20,000	$6,000+	$16,359
Link	https://www.dji.com/matrice600-pro/info#specs	https://www.sensefly.com/app/uploads/2018/09/eBee-X-EN.pdf	https://www.dji.com/phantom-4-rtk/info#specs	https://www.intel.com/content/www/us/en/drones/falcon-8-plus-brochure.html

*Quoted price is an estimate. Please contact the manufacturer to request a formal quote
NA - Not Available/Apparent; GCP – Ground Control Points Required; HA – Horizontal Accuracy; VA – Vertical Accuracy; GSD – Ground Sample Distance

4.5.5.1 Lidar Sensors

Lidar sensors are critical for collecting the required data to assist in surveying and mapping for highway design. Using UAS data for highway design places significant emphasis on the accuracy and the detail of the information collected from sensor payloads. Lidar sensors provide detailed digital information of the area being scanned in the form of 3D point clouds and surface models. This section reviews some of the commonly used products for lidar sensors.

Velodyne Lidar Sensors

Velodyne produces 3 lidar sensors for UAS with a full line of sensors capable of delivering the most accurate real-time 3D data on the market. Their sensors are developed to create a full 360-degree field of vision environmental view for use in autonomous vehicles, industrial equipment, 3D mapping and surveillance.

- HDL-32E Lidar Sensor

The HDL-32E lidar sensor is small, lightweight, ruggedly built and features up to 32 lasers across a 40-degree vertical field of view. The HDL-32E measures only 5.7” high x 3.4” in diameter, weighs less than 2 kg and was designed to exceed the demands of the most challenging real-world autonomous navigation, 3D mobile mapping and other lidar applications.

- Puck VLP-16 Lidar Sensor

Velodyne’s PUCK™ VLP-16 lidar sensor is the smallest, newest, and most advanced product in Velodyne’s 3D lidar product range. It is more cost-effective than similarly priced sensors and developed with mass production in mind.

Riegl Lidar Sensors

- The Riegl VUX-1UAV Lidar Sensor

The Riegl VUX-1UAV (formerly VUX-1) is a very lightweight and compact lidar laser scanner, meeting the challenges of emerging survey solutions by UAS/UAV/RPAS, both in measurement performance as in system integration.

- The RIEGL miniVUX-1UAV Lidar Sensor

The RIEGL miniVUX-1UAV is an extremely lightweight airborne laser scanner, designed specifically for integration with UAS/UAV/RPAS.

YellowScan Lidar Sensors

The YellowScan Mapper lidar sensor is a lightweight turn key surveying solution for UAS and other ultra-light aircraft. It’s a small size and ultra-light weight allow it to be mounted on most UAS.

- YellowScan Mapper
- YellowScan Surveyor

Geodetics Lidar Sensors

- Geo-MMS SAASM Drone Lidar Sensor

The Geodetics Geo-MMS SAASM is a fully integrated lidar mapping payload for integration with small unmanned vehicles. The Geo-MMS system includes an inertial navigation system, utilizing a SAASM GPS sensor with a path to M-Code, coupled with a lidar sensor.

Raw data from the integrated GNSS, IMU and lidar sensors are recorded on the internal data recording device and can be post-processed using Geodetics' lidar tool software package to directly geo-reference the lidar point clouds.

4.6 Public Engagement and Outreach (Rhode Island DOT)

Public involvement is a critical component in the transportation decision-making process, allowing for meaningful consideration and input from interested individuals. Early and strong public engagement has the potential to accelerate project delivery by helping identify and address public concerns early in the planning process, thereby reducing delays from previously unknown interests late in the project delivery process.

UAS use in public engagement can significantly enhance and increase public's awareness of opportunities and activities in Statewide plans and programs. From project visualization to construction safety, UAS can provide information from a completely different view point which can be more effective compared to existing methods.

4.6.1 Types of data

Currently, UAS is used dominantly in photography and videography when it comes to public engagement and outreach. There are more advanced technologies such as computer vision and data analysis applied to the UAS footage, but it is at an infant stage with little application. With the focus on media production to enhance project and program information dissemination and distribution, following list of type of data is available.

- **RGB Imageries/videos**: RGB imageries of project sites and aerial view of proposed plans can enhance visualization of an idea to the public. High resolution imagery and video is primary application for UAS use case in public outreach and engagement.
- **3D Models**: UAS fitted with laser scanners or RGB camera can reconstruct 3D model of an existing site with photorealistic detail. This model can be consumed with virtual reality or augmented reality which initiate public interest and involvement.
- **Infrared images:** Although not commonly used for public engagement, radiometric images can help people understand existing problems and issues identifiable with thermal sensors.
- **Traffic data**: Traffic flow and pattern analysis is one of the most recent application of UAS footage. Videos captured at a high altitude can be used to extract valuable traffic data which can help public to understand existing traffic problems.

4.6.2 Specific Criteria for UAS selection for public engagement and outreach

Use of UAS for public engagement and outreach does not require sophisticated system as it does with other engineering related applications. Instead, simple and easy operation can be the most important factor when choosing the right UAS system for public engagement and outreach. Most of commercially available UAS have similar specifications and capabilities. Considering these factors

The criteria identified below identifies cost effective and easy to operate system with a high-resolution video and still photo camera (at-least 12 MP; 38 MP desirable). Other major attributes for evaluation are enlisted below.

- **Platform type:** UAS platform type for public engagement and outreach must consider simple and easy operation. Copter type UAS platform is more stable, easy to operate and maneuverable than the fixed wing type.
- **RGB camera resolution:** Most of available UAS system comes with standard RGB camera that varies in resolution. Low end UAS system starts with 12 MP camera with 1080 HD video quality and it scales up to 20MP camera with 4K video quality. 20MP RGB camera with 4K video capability at 60 frames per second is recommended.
- **Flight duration**: The aircraft should have a flight time of at least 20 minutes (desirably around 45 minutes) with a fully charged battery to support autonomous operations. Longer duration is usually preferred but shorter duration (of around 20-25 mins) with multiple sets of battery would suffice.
- **Pre-processing and post-processing kits**: The aircraft should come equipped with a compatible flight control software system that can be used to plan and monitor autonomous flights. Preferably, the UAS should also come bundled with a processing software to analyze the collected data and produce necessary outputs for media production.

4.6.3 Operational requirements for public engagement and outreach

FAA's Part 107 regulations that govern the use of small UAS provides greater flexibility for commercial operations of the technology for bridge inspection purpose. These rules apply to UAS weighing less than 55lbs, operated within VLOS, using a pilot (who is FAA remote pilot certified) and flown in daylight hours and in the Class "G" airspace. On a few occasions, construction inspection may require certain deviations to these norms and such deviations must be authorized through waivers. Example include monitoring construction jobsites during night times, deploying UAS for construction inspection on sites that are near airports. With the evolution of the LAANC (Low Altitude Authorization and Notification Capability) system the FAA response time has been greatly curtailed allowing the flight operators to comply with the regulations easily.

4.6.4 Support systems for UAS integration into Public Engagement and Outreach

Transportation agencies needed to any software system necessary to support flight planning, control and post-processing of flight data collected from UAS. As public engagement and outreach activities commonly support agencies objectives in securing public trust and support for projects, standard desktop or cloud-based solutions capable of handling images and video-data from UAS is sufficient to ensure deployment of UAS.

In terms of hardware and platform capabilities, an internet search was conducted to identify available manufacturers that had largest market share servicing transportation industry and developing UAS that would comply with the operational requirements and data needs identified for public engagement and outreach. Following list of UAS are compared.

- DJI Mavic 2 Pro

- DJI Inspire 2
- DJI Phantom 4 RTK
- 3DR H520-G
- Intel Falcon 8+DJI Phantom 4 Pro

Table 4.6 below compares the UAS mentioned above based on the evaluation criteria identified for deploying UAS for public engagement and outreach efforts. While the information is based on best available information from product sheets and specifications currently available, it is to be noted that product upgrades continue to happen in the market. As such, it is recommended to contact the concerned manufacturers regarding the latest specifications of the UAS systems while making procurement decisions.

Table 4.7. Comparison of UAS characteristics for selected UAS products for public engagement and outreach

Characteristics	DJI Mavic 2 Pro	DJI Inspire 2	DJI Phantom 4 RTK	3DR H520-G	Intel Falcon 8+
Type	Quadcopter	Quadcopter	Quadcopter	Hexacopter	Octocopter
Weight	NA	3.44 kg (7.58 lbs.)	NA	1.645 kg	1.2 kg (2.65 lbs.)
Payload + Weight	0.907 kg	4.25 kg (9.37 lbs.)	1.39 kg	2 kg	2.0 kg (4.4 LBS)
Wind resistance	18 - 23 mph	23 mph	NA	NA	27 mph
Ingress Protection	NA	NA	NA	NA	NA
Range	Typically, 5-10 km	Up to 7KM	NA	NA	up to 1km
Altitude	NA	NA	NA	500 m	4000m (13,123 FT)
Operating temperature	0 to 40 deg Celsius	-20 to 40 deg Celsius	0 to 40 deg Celsius	-10 to 40 deg Celsius	-5 to 40 deg Celsius
Launching/ Landing Mechanism	None	None	None	None	None
Payload - Images/FOV	5247 X 3648	24MP / 300 degrees H and 180 degrees V	20MP	20 MP	36MP
Payload – Videos	3840 x 2160	6016 x 3200 (ProRes)	3840 x 2160 3p	4000 @6FPS	HD (1920x 1080)
Payload – Thermal/FOV	NA	Swappable	NA	NA	NA
Payload – SAR/Others	NA	Swappable	Yes	NA	Near-Infrared camera
Payload – Gimbal	Yes, not 360 deg	Yes	Yes, not 360 deg	Yes, not 360 deg	Yes, not 360 deg
Payload – Camera Shutter	Electronic	NA	Mechanical	Rolling	NA
Ground Control Points	Yes	Yes	No, RTK enabled	No, RTK enabled	Yes
HA/VA	NA	NA	NA	NA	NA

Characteristics	DJI Mavic 2 Pro	DJI Inspire 2	DJI Phantom 4 RTK	3DR H520-G	Intel Falcon 8+
GSD	NA	Varies	6.5cm/px	NA	NA
Flight duration	31 mins	25 mins	Up to 30 mins	28 mins	16-26 mins
Obstacle Avoidance	Yes	Yes	Yes	Yes	Yes
Pre-processing /Flight planning, controls	DJI Terra, FlightHub, GS Pro	DJI Terra, FlightHub, GS Pro	DJI Terra, FlightHub, GS Pro	DJI Terra, FlightHub, GS Pro	Yes
Post-processing/Data Analysis	DJI Terra, FlightHub, GS Pro	DJI Terra, FlightHub, GS Pro	DJI Terra, FlightHub, GS Pro	DJI Terra, FlightHub, GS Pro	NA
Price*	$1,729	$3,499	$6,000+	$6,000+	$16,359
Link	https://www.dji.com/mavic-2/info#specs	https://www.dji.com/inspire-2/info#specs	https://www.dji.com/phantom-4-rtk/info#specs	https://3dr.docsend.com/view/mbqgj36	https://www.intel.com/content/www/us/en/drones/falcon-8-plus-brochure.html

*Quoted price is an estimate. Please contact the manufacturer to request a formal quote
NA - Not Available/Apparent; GCP – Ground Control Points Required; HA – Horizontal Accuracy; VA – Vertical Accuracy; GSD – Ground Sample Distance

4.7 Emergency Response and Recovery (Vermont Agency of Transportation)

The 2040 Long Range Transportation Plan of the Vermont Transportation Agency (VTrans) places significant emphasis on next generation technologies such as autonomous vehicles, 5G networks, and UAS and their transformative impact on design, construction, and management of transportation system. Technologies such as UAS has a strong role to play in assisting state agencies respond to natural disasters through data collection for damage assessment studies, relief and rescue missions, and providing general reconnaissance efforts. The VTrans UAS program supports this application besides promoting the use to perform detailed mapping and survey products. It will help the agencies collect valuable data in a safe and cost-effective manner to mitigate the impact of the natural disasters on human life and property.

Task 1 identified utilizing UAS for emergency response as a key area of interest for VTrans. This section examines the primary data collection requirements to accomplish the objectives of deploying UAS for a natural disaster response and the ability of an UAS to support these objectives. Specific criteria to be used for selecting a commercially available UAS for emergency response are also described. Available products from top manufacturers in the market were compared based on the highlighted criteria.

4.7.1 Types of data

Deployment of UAS for emergency response has risen considerably owing to technological advancements in hardware, software and enabling regulatory framework. UAS can also provide safe and cost-effective mission to collect required data and perform rescue operations wherein human access is dangerous. Responding to emergencies such as flooding, wildfires, landslides and other events require detailed information to assess the complete extent of the damage and devise appropriate mitigation strategies.

Such data can be conveniently collected by deploying sensors on a UAS to survey the areas with adequate spatial and temporal resolution in a cost-effective manner.

The various types of data often needed for emergency response for natural disasters is explained below. to support various cases that are of interest to VTrans' UAS program (and its objectives).

- **RGB Imageries and videos**: High-resolution cameras collecting imageries and providing live video feeds provide valuable resource to assess extent of damage caused due to a natural disaster and develop appropriate repair and rehabilitation efforts. Collecting imageries during major natural calamity (such as hurricanes, flooding) is often the best alternative where manned aircraft missions are infeasible.
- **Infrared images**: These images are often captured using Forward Looking Infrared Cameras (FLIR), thermal infrared cameras or and multispectral and hyperspectral visible and near-infrared cameras. Infrared images can also be obtained through Short Wave Infrared Band (SIWR) band of optical sensors. They can be used to assess damage to the vegetation, wildlife, and monitor hot spots in the region of wildfires.
- **3D models**: 3D point clouds are usually collected using laser scanners deployed in UAS and used to produce high-resolution point clouds and digital surface models (DSMs). These models can assist in estimating volumetric information to quantify damages (such as extent of flooding) and aid in survey and reconnaissance efforts for rescue, repair and rehabilitation efforts.

4.7.2 Specific Criteria for UAS selection for emergency response

As the use of UAS for emergency response matures and the market expands with a variety of UAS manufacturers and service providers supporting UAS operations, it becomes necessary to establish the defining criteria that can help decision-makers select optimal configuration for UAS to suit the objectives of application. Commercial deployment of UAS have proven to be safe and cost-effective in collecting detailed visual information and offering other benefits such as improved safety, enhanced onsite productivity, and ability to inspect confined spaces.

Based on reconciling the information from several case studies of UAS applications in transportation projects, the following criteria have been identified. It is also assumed that the UAS should, by default, should come with a high-resolution video and still photo camera (at-least 12 MP; 38 MP desirable). Other major attributes for evaluation are enlisted below.

- **Platform type:** UAS platform type assumes significance for emergency relief and response efforts. Fixed wing aircrafts are used for studies that require longer flight time for damage assessment and reconnaissance; However, VTOL platforms are more often used to perform data collection and assist in rescue efforts in space constrained environments.
- **Payload Attachments**: The UAS should be flexible to accommodate or swap a variety of payloads especially cameras or sensors to collect imageries or information of different types.
- **Flight duration**: The aircraft should have a flight time of at least 45 minutes with a fully charged battery to support autonomous operations. This is important to ensure launching UAS in a constrained environment from safety and accessibility perspective.

- **Obstacle Avoidance**: The craft should have the ability to detect obstacles and automatically prevent itself from flying into or being flown into an obstacle to mitigate the possibility of a crash.
- **Pre-processing and post-processing kits**: The aircraft should come equipped with a compatible flight control software system that can be used to plan and monitor autonomous flights. Preferably, the UAS should also come bundled with a processing software to analyze the collected data and produce necessary outputs for emergency response.

4.7.3 Operational requirements for emergency response

FAA's Part 107 regulations that govern the use of small UAS provides greater flexibility for commercial operations of the technology for emergency management purpose during natural disasters. These rules apply to UAS weighing less than 55lbs, operated within VLOS, using a pilot (who is FAA remote pilot certified) and flown in daylight hours and in the Class "G" airspace. However, launching UAS for emergency management may require certain deviations to these norms and such deviations must be authorized through waivers. Example include conducting relief missions during night times, operating UAS beyond VLOS, and launching UAS in locations that are near airports.

With the rapid development of UAS technology, VTrans UAS is looking forward to working with and assisting many new successful applications across state government including emergency responders and law enforcement agencies. interagency agreements (e.g. memorandums of agreement/understanding) can be structured to incorporate specific UAS tasking protocols to ensure UAS technology is an integral part of the planning and eventual response/recovery efforts.

4.7.4 Support systems for UAS integration into Emergency Response

According to National Incident Management System (NIMS) and FEMA's National Public agencies intending to deploy UAS for emergency response need to devise a Common Operating Picture (COP), a real-time situational awareness platform across all levels of incident managements and jurisdictions A COP benefits by providing accurate and real-time information regarding equipment distribution, response personnel location, onsite intelligence, and incident mapping for ensuring timely response to incidents and minimize the resultant impact. Administering UAS for emergency response can help agencies achieve the objectives of a COP framework. Public agencies can rely on the System Assessment and Validation for Emergency Responders (SAVER) Program established by The U.S. Department of Homeland Security (DHS) established the to assist emergency making procurement decisions. The SAVER Program includes small Unmanned Aerial Systems (UAS) in their Authorized Equipment Lists (AELs) for facilitating emergency response and provides general guidelines on types of UAS and operational requirements for using them (U.S. Department of Homeland Security, 2008).

In terms of hardware and platform capabilities, an internet search was conducted to identify available manufacturers that had largest market share servicing transportation industry and developing UAS that would comply with the operational requirements and data needs identified for emergency response. Following list of UAS are compared.

- DJI Mavic 2 Pro
- DJI Inspire 2
- DJI M210 Series V2/RTK

- Intel Falcon 8+
- SenseFly eBee X

Table 4.5 compares the UAS mentioned above based on the evaluation criteria identified for deploying UAS for emergency response. While the information is based on best available information from product sheets and specifications currently available, it is to be noted that product upgrades continue to happen in the market. As such, it is recommended to contact the concerned manufacturers regarding the latest specifications of the UAS systems while making procurement decisions.

Table 4.8. Comparison of UAS characteristics for selected UAS products for emergency response

Characteristics	DJI Mavic 2 Pro	DJI Inspire 2	DJI M210 Series V2/RTK	Intel Falcon 8+	SenseFly eBee X
Type	Quadcopter	Quadcopter	Quadcopter	Octocopter	Fixed Wing
Weight	NA	3.44kg (7.58 lbs.)	4.69 kg	1.2kg (2.65 lbs.)	NA
Payload + Weight	0.907kg	4.25 kg (9.37 lbs.)	6.14 kg	2.0kg (4.4 LBS)	1.4Kkg (3.1 lbs.)
Wind resistance	18 - 23 mph	23 mph	27 MPH	27 mph	Up to 29mph
Ingress Protection	NA	NA	IP43	NA	NA
Range	Typically, 5-10 km	Up to 7 km	Na	Up to 1 km	Up to 30 miles (communication range up to 3.1 miles)
Altitude	NA	NA	NA	4000 m (13,123 FT)	NA
Operating temperature	0 to 40 deg Celsius	-20 to 40 deg Celsius	-20 to 50 deg Celsius	-5 to 40 deg Celsius	-10 to 40 deg Celsius
Launch/ Landing Mechanism	None	None	None	None	Hand Launch/Belly Landing
Payload - Images/FOV	5247 X 3648	24MP (Zenmuse X7)	24MP / 300 degrees H and 180 degrees V	36MP	Multiple SenseFly Cameras
Payload - Videos	3840 x 2160	6016 x 3200 (ProRes)	6016 x 3200 (ProRes)	HD (1920x 1080)	NA
Payload - Thermal/FOV	NA	NA	Swappable	NA	NA
Payload - SAR/Others	NA	NA	Swappable	Near Infrared camera	NA
Payload - Gimbal	Yes, not 360 deg	Yes	Yes, not 360 deg	Yes, not 360 deg	No
Payload - Camera Shutter	Electronic	NA	Electronic and Mechanical	NA	Global
GCP	Yes	Yes	No, RTK enabled	Yes	No, with included High-Precision on Demand (RTK/PPK)

Characteristics	DJI Mavic 2 Pro	DJI Inspire 2	DJI M210 Series V2/RTK	Intel Falcon 8+	SenseFly eBee X
HA/VA	NA	NA	NA	NA	Up to 3cm
GSD	NA	NA	Varies	NA	2.5 cm/px (1.0 in/px) at 400FT
Flight duration	31 mins	25 mins	24 mins	16-26 mins	Up to 90 mins
Obstacle Avoidance	Yes	Yes	Yes	Yes	No
Pre-processing /Flight planning, controls	DJI Terra, FlightHub, GS Pro	DJI Terra, FlightHub, GS Pro	DJI Terra, FlightHub, GS Pro	Yes	eMotion
Post-processing/Data Analysis	DJI Terra, FlightHub, GS Pro	DJI Terra, FlightHub, GS Pro	DJI Terra, FlightHub, GS Pro	NA	Pix4D, Agisoft, Trimble Business Center
Price*	$1,729	$3,499	$6,000+	$16,359	~20,000
Link	https://www.dji.com/mavic-2/info#specs	https://www.dji.com/inspire-2/info#specs	https://www.dji.com/matrice-200-series-v2/info#specs	https://www.intel.com/content/www/us/en/drones/falcon-8-plus-brochure.html	https://www.sensefly.com/app/uploads/2018/09/eBee-X-EN.pdf

*Quoted price is an estimate. Please contact the manufacturer to request a formal quote

NA - Not Available/Apparent; GCP – Ground Control Points Required; HA – Horizontal Accuracy; VA – Vertical Accuracy; GSD – Ground Sample Distance

5.0 CONCLUSION

The selected transportation applications present unique requirements for using UAS as a support tool for traditional workflows. The availability of reliable and proven UAS hardware and software technology in the marketplace offer DOTs access to powerful technology that delivers value from reducing safety risks to streamlining project delivery. Existing IT capability and infrastructure at DOTs can be leveraged to initiate a UAS program; however, enhancements are recommended to ensure a sustainable and successful UAS program. Furthermore, as the UAS program fleet and crew size increases, physical space for equipment storage and maintenance will be required including a secure room for charging batteries, aircraft maintenance, and space for researching and testing system functionality.

Other tertiary equipment that is necessary for UAS operations include a generator, hand radios, cell phones, removable data storage media (e.g. SD cards, external hard drives, etc.), targets, and surveying equipment for measuring positions of ground control (as needed). Several DOTs such as Alabama DOT have invested in a mobile command and control center to serve as a communication and data hub for their UAS operations. The center is a fully enclosed trailer with an 8,000-kilowatt generator and 100 gallons of fuel, which provides enough power for about a week. Other features include a server rack, Wi-Fi, communication links, UAS repair area, storage areas, spare parts and tools, UAS takeoff and landing pad, microwave and refrigerator, and workstation areas for data processing.

The following table describes recommended specifications for UAS hardware necessary for the selected transportation applications. These specifications may be able to be accommodated using a fleet of UAS rather than a single system. Some of the specifications are situational depending on the environmental conditions at the time of the UAS mission.

Table 5.1. Recommended specifications for UAS hardware in support of transportation applications.

Characteristics	Bridge Inspection	Construction Inspection	Traffic Analysis	Surveying and Mapping	Public Engagement	Emergency Response
Aircraft Type	Rotary (8 propellers)	Rotary (4 propellers) and fixed-wing	Rotary (4 propellers)	Rotary (8 propellers) and fixed-wing	Fixed-wing	Rotary (4 propellers) and fixed-wing
Wind Resistance	25 mph	15 mph	10 mph	25 mph	10 mph	25 mph
Minimum Ingress Protection	IP43	IP43	IP43	IP43	Any	IP43
Operating Temperature	-20 to 50 deg Celsius	-20 to 50 deg Celsius	-20 to 50 deg Celsius	-20 to 50 deg Celsius	n/a	-20 to 50 deg Celsius
Payload Sensors	RGB, EO/IR, thermal	RGB and lidar	RGB and thermal	RGB, EO/IR, lidar, radar	RGB	RGB, EO/IR, thermal, lidar, radar
Positioning Type	Any	RTK/GCP	Any	RTK/GCP	Any	RTK/PPK
RMSE (r/v)	<3 cm/<3 cm	<3 cm/<3 cm	<5 cm/<5 cm	<3 cm/<3 cm	<1 m/ <4 m	<5 cm/<5 cm
GSD	<1 cm	<1 cm	<5 cm	<1 cm	<1 m	<5 cm

Characteristics	Bridge Inspection	Construction Inspection	Traffic Analysis	Surveying and Mapping	Public Engagement	Emergency Response
Camera Shutter	Global (mechanical)	Global (mechanical)	Rolling (electronic)	Global (mechanical)	Rolling (electronic)	Rolling (electronic)
Minimum Flight Duration	45 min.	30 min.	45 min.+	45 min.	30 min.	45 min.
Obstacle Avoidance/ Collision Tolerant	Yes	No	No	Yes	No	Yes
Batteries (available per mission)	10+	10+	10+	10+	4	10+
Data Quality Oversight	Bridge Inspector with UAS pilot	PLS or CP with Resident/Area Engineer	UAS Pilot	PLS or CP	UAS Pilot	Emergency Manager with UAS pilot

RMSE – root-mean-square Error (measure of positional accuracy); $RMSE_r$ – radial (combined coordinate position) error; $RMSE_V$ – vertical error; PLS – state-licensed Professional Land Surveyor/Mapper; CP – ASPRS Certified Photogrammetrist

State DOTs should look at using proprietary flight planning and control applications provided by the UAS manufacturers to seamlessly integrate with aircraft avionics. This ensures reliability and confidence in flight control using more automated production of flight parameters. However, procuring UAS platforms manufactured by different vendors will likely result in using multiple applications. As a supplement to proprietary flight planning applications, there are web-based sources of validation data for NOTAMs, aeronautical charts, and weather data that should become an integral part of the flight planning process.

It is recommended that state DOTs leverage their enterprise license agreement (if available) with major CAD software vendors, such as Bentley and Autodesk, to gain access to UAS data processing modules/applications (e.g. Bentley ContextCapture, Autodesk Recap, etc.). Cloud-based UAS data processing applications provide a quick and easy to use platform for creating various products; however, these applications generally sacrifice data quality (accuracy and integrity) and processing control, which may be important for higher accuracy requirements. Desktop client UAS data applications are more resource-intensive and generally have more power and transparency to deliver sufficient data quality for most applications. Consulting with UAS data processing experts (internally or externally) is a prudent option to manage data quality and cost for advanced UAS operations.

In order to accommodate collecting, processing, storing, and managing large volumes of UAS data, state DOTs should look to improve their IT infrastructure and workstation capability. Having dedicated server capacity and resources will help state DOTs process and store large data volumes and velocities without compromising other enterprise systems. Table 5.2 provides specifications and recommendations on IT infrastructure and the primary UAS data processing workstation requirements.

Table 5.2. Recommended IT infrastructure and workstation specifications for UAS operations.

Characteristics	Recommendations
Dedicated Cloud Server	Yes
Dedicated On-premises Server	Yes (with redundancy)
Deep Learning Technology Stack	Yes, for advanced UAS programs.
Networking	10 GB intranet/1 GB internet
Workstation Processing	3 GHz (8 core)
Workstation Storage	500 GB
Workstation Memory	16 GB SSD
Workstation Graphics	2000+ processing cores; 6GB GDDR6 RAM
Workstation Display	2x monitors
Workstation Interfaces/Ports	11x USB 3.1 ports; 2x ethernet ports; HDMI ports
Policy/Legal	Establish cloud computing policy that allows users to access and download data from third-party cloud services. Establish workable service level agreements and contractual terms with vendors favorable to UAS operations. Also, establishing partnerships with IT authorities will ensure

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7.0 APPENDIX A (INDUSTRY QUESTIONNAIRES)

The research team design and distributed several industry questionnaires to understand certain elements of current technologies and support systems used for commercial UAS operations. The questionnaires also touched on certain process challenges such as securing necessary waivers. The National Business Aviation Administration (NBAA), American Association of State Highway Transportation Officials (AASHTO), and the American Society of Photogrammetry and Remote Sensing (ASPRS), were identified as important industry communities to solicit feedback on specific aspects. The NBAA questionnaire intended to capture a general understanding of commercial UAS mission planning and program elements (including support systems) used in support of state departments of transportation operations. The AASHTO questionnaire intended to capture a general understanding of the viability of using commercial UAS technology for data-driven decision making in support of state departments of transportation operations. Lastly, the ASPRS questionnaire intended to capture a general understanding of commercial UAS technology data governance and processing in support of state departments of transportation operations.

Unfortunately, the current number of responses to each of the questionnaires is low for several potential reasons including limited time to respond and lack of understanding of research effort; however, the questionnaires will remain active and any subsequent feedback will be integrated into relevant areas.

7.1 National Business Aviation Administration

The NBAA is a leading organization for companies that rely on general aviation aircraft to help make their businesses more efficient, productive and successful and represents more than 11,000 companies and professionals. The questionnaire was distributed through the NBAA Emerging Technologies Committee given its mission to drive future aviation safety and policy with emerging aviation technologies such as UAS. The questions are listed below for reference.

What is your primary area of expertise?

- Aviation/Aeronautics
- Policy
- Legal
- Information technology
- Manufacturing
- Software/Application development
- Emergency management
- Public safety
- Public administration
- Planning
- Standards
- Military
- Education
- Other

How many years' experience do you have in working with sUAS technology and related systems?

- 0-5
- 5-10
- 10-20

What is your role?

- Federal agency
- State agency
- Local agency
- Consultant
- Software/Application Vendor
- Manufacturer
- Academia
- Industry association
- Other

Which sUAS safety management system component(s) have you implemented?

- sUAS safety policy
- sUAS safety assurance processes
- sUAS safety promotion/culture/training

How effective is your sUAS safety management system? Please rate effectiveness (1 – not effective, 2 – somewhat effective, 3 – neutral, 4 – mostly effective, 5 – highly effective).

Rank the sUAS flight planning software in the US by preference (1 – low, 2 – medium, 3 – high).

- Airmap
- Esri ArcGIS
- iFlightPlanner
- Photomodeler
- PrecisionHawk PrecisionFlight
- senseFly eMotion
- Skyvector
- Skyward
- UgCS
- Yuneec DataPilot
- Kittyhawk
- Other

How effective is your sUAS flight planning software? Please rate effectiveness (1 – not effective, 2 – somewhat effective, 3 – neutral, 4 – mostly effective, 5 – highly effective).

Rank each of the application/service suppliers for providing airspace authorizations for sUAS operations in the US by preference (1 – low, 2 – medium, 3 – high).

- FAA DroneZone
- Aeronyde
- Airbus
- Airmap
- AiRXOS
- Altitude Angel
- Converge
- DJI
- Harris Corporation
- Kittyhawk
- Project Wing
- Skyward
- Thales Group
- UASidekick
- Unifly
- Other

How effective is your application/service suppliers for providing airspace authorizations for sUAS operations? Please rate effectiveness (1 – not effective, 2 – somewhat effective, 3 – neutral, 4 – mostly effective, 5 – highly effective).

Rank each of the sUAS flight applications in the US by preference (1 – low, 2 – medium, 3 – high).

- DJI Go
- DJI Pilot
- DJI GS Pro
- Litchi
- DroneDeploy
- DroneHarmony
- AutoPilot
- Skywatch
- MapPilot
- UltimateFlight
- TopPilot
- Pix4D
- Kittyhawk
- Other

How effective is your sUAS flight application(s)? Please rate effectiveness (1 – not effective, 2 – somewhat effective, 3 – neutral, 4 – mostly effective, 5 – highly effective).

Have you applied for a Part 107 waiver?

- Yes

- No

How many Part 107.29 (daylight ops) waivers do you apply for each year?

- 0
- 1-5
- 5+
- I have not yet applied for this waiver.

In general, how long does it take to apply for and obtain a Part 107.29 (daylight ops) waiver?

- 0 – 30 days
- 30 – 60 days
- 60 – 90 days
- 90+ days

How many Part 107.31 (visual line of sight) waivers do you apply for each year?

- 0
- 1-5
- 5+
- I have not yet applied for this waiver.

In general, how long does it take to apply for and obtain a Part 107.31 (visual line of sight) waiver?

- 0 – 30 days
- 30 – 60 days
- 60 – 90 days
- 90+ days

How many Part 107.33 (visual observer) waivers do you apply for each year?

- 0
- 1-5
- 5+
- I have not yet applied for this waiver.

In general, how long does it take to apply for and obtain a Part 107.33 (visual observer) waiver?

- 0 – 30 days
- 30 – 60 days
- 60 – 90 days
- 90+ days

How many Part 107.35 (multiple sUAS) waivers do you apply for each year?

- 0
- 1-5

- 5+
- I have not yet applied for this waiver.

In general, how long does it take to apply for and obtain a Part 107.35 (multiple sUAS) waiver?

- 0 – 30 days
- 30 – 60 days
- 60 – 90 days
- 90+ days

How many Part 107.39 (ops over people) waivers do you apply for each year?

- 0
- 1-5
- 5+
- I have not yet applied for this waiver.

In general, how long does it take to apply for and obtain a Part 107.39 (ops over people) waiver?

- 0 – 30 days
- 30 – 60 days
- 60 – 90 days
- 90+ days

How many Part 107.51b (ops limits – altitude) waivers do you apply for each year?

- 0
- 1-5
- 5+
- I have not yet applied for this waiver.

In general, how long does it take to apply for and obtain a Part 107.51b (ops limits – altitude) waiver?

- 0 – 30 days
- 30 – 60 days
- 60 – 90 days
- 90+ days

Please note any other information that may be useful in understanding the integration of sUAS technology.

7.2 American Association of State Highway Transportation Officials

AASHTO is a nonprofit, nonpartisan association representing highway and transportation departments in the 50 states, the District of Columbia, and Puerto Rico. Its primary goal is to foster the development, operation, and maintenance of an integrated national transportation system. AASHTO works to educate the public and key decision makers about the critical role that transportation plays in securing a good quality of life and sound economy for our nation and serves as a liaison between state departments of transportation and the Federal government. AASHTO is an international leader in setting technical standards for all phases of highway system development including the design, construction of highways and bridges, materials, and many other technical areas. The questionnaire was distributed through various AASHTO committees including Research and Innovation, Transportation System Operations, Design, and Construction. The questions are listed below for reference.

What is your primary area of expertise?

- Research
- Bridge Inspection
- Construction Oversight
- Construction Inspection
- Highway Design
- Bridge Design
- Transportation Operations
- Maintenance
- Asset Management
- Emergency Management
- Aviation/Aeronautics
- Intelligent Transportation Systems
- Other

How many years of transportation experience do you have?

- 0-5
- 5-10
- 10-20
- 20-30
- 30+

What is your role?

- Agency/Owner
- Consultant
- Contractor
- Federal
- Industry Association
- Other

Have you used sUAS technology in support of your routine mission requirements?

- Yes
- No
- Unknown

Have you used sUAS technology in support of on-off mission requirements (e.g. emergent or unique situations)?

- Yes
- No
- Unknown

Of these broad areas of application, where do you see sUAS technology creating value? Select all that apply.

- Routine data collection of frequent tasks
- Situational data collection (e.g. emergencies/incidents)
- Visualization/communication for public
- Other

What are the main barriers to testing the use of sUAS in support of decision making? Select all that apply.

- Insufficient understanding of capability
- Lack of confidence in data quality
- Regulations
- Policy
- Liability
- Other

Are your staff generally receptive to using sUAS technology in support of their activities?

- Yes
- No
- Maybe
- Unknown

To what extent do data compliance requirements (e.g. inspection requirements) limit use of sUAS technology? Please indicate level of limitation (1 – not applicable, 2 – significantly, 3 – moderately, 4 – not at all).

To what extent do sUAS technology limitations (e.g. software/hardware resiliency) negatively impact workflows? Please indicate level of limitation (1 – not applicable, 2 – significantly, 3 – moderately, 4 – not at all).

To what extent do regulatory limitations of sUAS mission capability (e.g. need for special waivers) negatively impact workflows? Please indicate level of limitation (1 – not applicable, 2 – significantly, 3 – moderately, 4 – not at all).

What opportunities exist to incorporate sUAS operations and/or data into your decision support system?

- Equipping staff with knowledge and understanding of sUAS operations and data
- Equipping staff with sUAS technology and required credentials
- Providing on-demand/as-needed access to sUAS technology through partnerships or outsource

- Other

Are you currently integrating sUAS data with GIS?

- Yes
- No
- Unknown

Does your agency have a formal sUAS program in place?

- Yes
- No
- Unknown

Does your agency have training requirements in place that exceed those required by the FAA Part 107 certification process?

- Yes
- No
- Unknown

Do you actively collaborate with emergency responders through data sharing, joint preparedness exercises, or general coordination/awareness?

- Yes
- No
- Unknown

If using consultants/contractors for sUAS missions, do you maintain an in-house UAS program administrator to coordinate necessary resources and policy needs?

- Yes
- No
- Unknown

What factors have influences purchasing decisions for sUAS technology? Select all that apply.

- Ease of use for specific applications
- Cost
- Recommendations from trusted sources
- Results from pilot project(s)
- Other

What sUAS technology advancements are expected to arrive by 2022 that will improve sUAS operations and data capture/processing? Select all that apply.

- Georeferencing systems
- sUAS platform resiliency/hardening

- Sensor capability
- Cybersecurity/data integrity and resiliency
- Ground control station enhancements
- AI/Deep learning
- Edge computing
- Battery technology
- Propulsion technology
- Weather resistance
- Airworthiness standards
- Other

Please note any other information that may be useful in understanding where you see sUAS technology fit into your workflows.

7.3 American Society of Photogrammetry and Remote Sensing

ASPRS is a scientific association serving over 7,000 professional members and its mission is to advance knowledge and improve understanding of mapping sciences to promote the responsible applications of photogrammetry, remote sensing, geographic information systems (GIS) and supporting technologies. The questionnaire was distributed through the ASPRS executive office to membership. The questions are listed below for reference.

What is your primary area of expertise?

- Surveying – Professional (PS, RPLS, PLS, LS, etc.)
- Surveying – Technician
- Photogrammetry/Remote Sensing – Professional (CP)
- Photogrammetry – Technician
- Remote Sensing – Technician
- Part 107 Pilot
- Advanced Modeling (GIS, CAD, BIM, etc.)
- Data Science
- Software/Application Development
- Manufacturing
- Other

How many years of transportation experience do you have?

- 0-5
- 5-10
- 10-20
- 30+

What is your role?

- Agency/Owner

- Consultant
- Contractor
- Federal
- Industry Association
- Software/Application Vendor
- Manufacturer
- Other

What software do you use for sUAS data processing? Select all that apply.

- Bentley ContextCapture
- Pix4D
- Hydra Fusion
- Trimble Inpho
- Esri Drone2Map
- DroneDeploy
- Agisoft Metashape
- 3DR
- Carinal Systems VR Mapping
- Skycatch
- Other

What sUAS platform do you use for structural inspection? Select all that apply.

- Helicopter
- Multicopter
- VTOL fixed wing
- Fixed-wing
- None
- Other

What sUAS platform do you use for site mapping? Select all that apply.

- Helicopter
- Multicopter
- VTOL fixed wing
- Fixed-wing
- None
- Other

What sUAS platform do you use for emergency/incident response (damage assessment, situational awareness, risk assessment, etc.)? Select all that apply.

- Helicopter
- Multicopter

- VTOL fixed wing
- Fixed-wing
- None
- Other

What sUAS platform do you use for public engagement and outreach? Select all that apply.

- Helicopter
- Multicopter
- VTOL fixed wing
- Fixed-wing
- None
- Other

What sUAS platform do you use for traffic analysis (speed limiting, work zone management, etc.)? Select all that apply.

- Helicopter
- Multicopter
- VTOL fixed wing
- Fixed-wing
- None
- Other

What sUAS platform do you use for construction inspection support? Select all that apply.

- Helicopter
- Multicopter
- VTOL fixed wing
- Fixed-wing
- None
- Other

What sensors do you own and use? Select all that apply.

- RGB imagery (video)
- RGB imagery (still)
- Lidar
- Radar (SAR, GPR, etc.)
- Hyperspectral
- Multispectral
- Infrared
- Near-infrared
- Thermal
- Other

How close are the following platform manufacturer specifications to actual performance/capability? Please indicate accuracy (1 – inaccurate, 2 – mostly inaccurate, 3 – neutral, 4 – mostly accurate, 5 – highly accurate).

- Weight
- Weight + Payload
- Flight range
- Flight speed
- Altitude
- Operating temperature
- Wind resistance rating
- Weather resistance rating

How close are the following sensor manufacturer specifications to actual performance/capability? Please indicate accuracy (1 – inaccurate, 2 – mostly inaccurate, 3 – neutral, 4 – mostly accurate, 5 – highly accurate).

- Horizontal field of view
- Vertical field of view
- Horizontal accuracy without ground control
- Vertical accuracy without ground control
- Data resolution
- Ground sample distance
- Data capacity/transfer latency
- Operating temperature
- Gimbal functionality

How many Part 107 sUAS flights does your company complete each year?

- 0-10
- 10-30
- 30-70
- 70-100
- 100-150
- 150-200
- 200-300
- 300+

What are the major concerns with using sUAS technology? Select all that apply.

- Data quality
- Data accuracy (horizontal)
- Data accuracy (vertical)
- Ease of use
- System interoperability

- Flight command and control
- Airworthiness
- Data modeling standards
- Data security
- Take-off and landing
- Recovery
- Proprietary systems
- Confidence in flight/data parameters
- Other

What gimbals are used? Select all that apply.

- 2-axis
- 3-axis
- Fixed
- Gyrostabilized
- Other

How well does the IMU compensate for POS affects? Please indicate rating (1 – terrible, 2 – poor, 3 – fair, 4 – good, 5 – excellent).

What are your concerns with structure from motion algorithms? Select all that apply.

- Obscure processing/validation
- Data accuracy (horizontal)
- Data accuracy (vertical)
- Other

What sUAS technology advancements will arrive by 2022 that will improve operations and data capture/processing? Select all that apply.

- Georeferencing systems
- sUAS platform resiliency/hardening
- Sensor capability
- Cybersecurity/data integrity and resiliency
- Ground control station enhancements
- AI/Deep learning
- Edge computing
- Battery technology
- Propulsion technology
- Weather resistance
- Airworthiness standards
- Other

Which technology advancements will prove vital for improving sUAS operations and data/capture processing in the long-term? Select all that apply.

- Robotics/Automation
- 5G
- Cloud computing
- Edge computing
- AI/deep learning
- Federal of intelligent transportation systems, internet of things, and autonomous technology
- Other

Which georeferencing method yields best 3D accuracy from sUAS data?

- Post-processing kinematic (PPK)
- Real-time kinematic (RTK)
- Ground control points
- Integrated sensor orientation with PPK
- Integrated sensor orientation with RTK
- Other

Which PPK solution have you used? Select all that apply.

- Micro Aerial Projects V-map
- AirGon Loki
- EMLID Reach
- Other

Are you a state department of transportation employee?

- Yes
- No

The following questions were asked to only state department of transportation employees:

Does your agency have a chartered sUAS program?

- Yes
- No
- Unknown

What specific business requirements are sUAS meeting? Please select all that apply.

- Surveillance
- Surveying and mapping
- Pay item measurement/verification
- Inspection
- Traffic monitoring

- Construction progress monitoring
- Environmental assessment
- Other

Rank the importance of the following sUAS program benefits (1 – no benefit, 2 – minimal, 3 – moderate, 4 – good, 5 – excellent).

- Save time
- Save costs
- Increase Safety
- Decrease congestion
- Increase employee engagement
- Increased documentation quality
- Improved workforce development/retention
- Other

What are the challenges with implementing a sUAS program? Please select all that apply.

- Executive support
- Developing business case
- Identifying a champion
- Training
- Developing a strategy
- Purchasing the technology
- Funding
- Other

Have you used state funds for funding sUAS deployment/integration efforts?

- Yes
- No
- Unknown

Have you used state transportation innovation council (STIC) funds for funding sUAS deployment/integration efforts?

- Yes
- No
- Unknown

Have you used accelerated innovation deployment (AID) funds for funding sUAS deployment/integration efforts?

- Yes
- No
- Unknown

Have you used accelerated market readiness (AMR) funds for sUAS deployment/integration efforts?

- Yes
- No
- Unknown

Do you anticipate sUAS technology to be used on a consistent basis at your agency?

- Yes
- No
- Maybe
- Unknown

How are your sUAS missions being flown?

- In-house
- Contractor/Consultant/Outsource
- Both
- Not applicable

Do you own sUAS technology?

- Yes
- No
- Unknown
- Not applicable

If using consultants/contractors, does your agency have an internal process for validating data acquired by external parties?

- Yes
- No
- Unknown
- Not applicable

Are you actively sharing data collected by sUAS with other state agencies?

- Yes
- No
- Unknown
- Not applicable

Do you feel there are adequate technology solutions available to overcome challenges relating to environmental/climate conditions in your state?

- Yes
- No
- Unknown

- Not applicable

Do you feel that sUAS software vendors understand your challenges and are actively working to solve them?

- Yes
- No
- Unknown
- Not applicable

Do you feel that sUAS hardware vendors understand your challenges, and are actively working to solve them?

- Yes
- No
- Unknown
- Not applicable

What factors have influenced purchasing decisions for UAS technology?

- Ease of use for specific applications
- Cost
- Recommendations from trusted sources
- Results from pilot project(s)
- Other

Please note any other information that may be useful in understanding the integration of sUAS technology.