PNNL-25394

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Nuclear Safeguards Applications Employing Unmanned Airborne Vehicles

May 2016

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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830

UNCLASSIFIED

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operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

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1.0 Introduction

This paper describes some potential applications for UAVs (Unmanned Aerial Vehicles) in international nuclear safeguards. UAV missions can include indoor and outdoor operations including: 1) surveillance, which includes all types of sensors and imagers, 2) command and control augmentation (radio relays and real-time imagery used primarily to coordinate ground operations), and 3) physical sample collection and transport.

Most of the applications described in this paper involve surveillance or physical sample collection and transport. For example, high value applications may include appropriately configured UAVs that can acquire high definition digital imagery combined with object recognition software. Both 100% accounting of objects and, with digital change detection algorithms, tampering and movement could also be determined. UAVs with the right hardware may be valuable in collecting environmental or operational samples in locations where humans cannot easily reach or gain access. IAEA inspections under comprehensive safeguards agreements (CSA) and complementary access (CA) under the Additional Protocol (AP) could benefit from use of UAVs. The IAEA considers visual observation under CA to include the use of cameras.

Each application in this report has been notionally characterized in six categories to help facilitate decisions to pursue the development of these techniques. The scenario or **use condition** is categorized as Inspection or CA. The **existing IAEA authority** (either CSA or the applicable AP article) that would cover the use of each application technology is listed. The **fuel cycle stage** of the nuclear material development process is noted. And finally, three categories provide PNNL's assessment of status: I**mplementation priority** considers the perceived importance of the specific application**.** T**echnical readiness** relates to an engineering assessment of the amount of research and development that has already been accomplished and would support the application. High technical readiness means that a majority of the technology needed has been developed and can probably be purchased commercially – with only a systems integration effort needed to implement. Low technical readiness means that certain techniques and technologies would need to be developed, but are well within reach. **The probability of IAEA adoption** is PNNL's assessment that combines the application's fit within IAEA's authorities, the perceived need, the return on investment, and a general perception of how various stakeholders would respond to the introduction of the application.

2.0 Applications

The following table provides a summary of the applications for unmanned airborne systems described in this report.

Application	Priority	Tech. Readiness	Probable Adoption	Application Topic	Fuel Cycle Stage
1	H	H	H	Sample Unreachable Areas	All
2	H	H	M	Whole Site Camera – "Eye in the Sky"	All
3	H	M	H/M	Low Altitude Roaming – UAV Mounted Camera	All
4	H	M	M	UF_6 Container Counting / Cataloging	Conversion / Enrichment
5	H	M	M	Facility Design Verification	All
6	H	M	M	Spent Fuel Visual Inspection	Spent Fuel Storage
7	M	H	M	Yellowcake Barrel Counting / Cataloging	Refining - Conversion
8	M	L	M	Repositionable – UAV Mounted Camera	All
9	L	H	M	U Mine and Mill Production Assessment	Mine, Extraction & Refining
10	L	M	H	Nuclear Waste Repository Mapping and Change Det.	Waste Storage
11	L	M	M	Corrosive Process Sampling	Reprocessing

2.1 Sample Unreachable Areas

Use Condition: CA with inspector present, or stationary environmental sampling. At locations declared under the AP, and other locations.

Existing IAEA authority: AP Articles 2a, 2b / 6a, 6b, 6c, 6d.[1] (Environmental sampling)

Fuel Cycle Stage: All

Implementation Priority: High

Technical Readiness: High

Probable IAEA Adoption: High

During inspections or CAs, inspectors can utilize UAVs to sample areas that are not easily within reach of human inspectors. Areas could include ceilings, high piping, duct work and confined spaces. Small quadcopters are available today at very low cost. These vehicles can be easily piloted indoors or outdoors by inspectors with little specific training. This concept proposes that small aerial robots could be outfitted with swabs, mini-vacuums, and other sample collecting and interrogating devices. Inspectors would be able to conduct a more thorough investigation by acquiring samples from overhead or hard to reach locations that might be missed during a cleaning process executed by proliferators. If an inspector can perform a swipe that will collect particles yielding a positive result, than a state can apply and repeat the same "collection" technique in advance of an inspection; presenting perfectly clean surfaces, essentially free of particles. Cleaning, to this degree, all surfaces within reach of an

[1] The first number (before the slash) refers to the AP article under which the location is declared. The second number refers to the AP article that identifies the associated CA measures allowed.

inspector would be a significant achievement for a proliferator; but to clean all surfaces available to a flying UAV would be a monumental effort in many cases. The daunting inevitability of a drone inspection would, perhaps, be a significant deterrent to the plans of a proliferator. It may also be true that using a UAV to collect samples at elevation or in difficult to reach areas will intrinsically enhance the safety of the sampling operation; reducing risk to the inspector and supporting facility staff. Statistical sample coverage will be more easily achieved with the use of UAVs to collect samples from nearly any surface in a room.

With an overall weight of less than two pounds, these indoor drones are very unlikely to have the ability to cause any damage. Use by an inspector who is present using a UAV for this purpose is judged to be relatively acceptable to the State and facility/location operator. Small UAVs could even be tethered with a small line to provide assurance that the vehicle does not operate outside the intended area.

A similar operation to collect samples at altitude may include outdoor dust collections on the sides of buildings where facility exhaust particulate may collect. Swab samples could be taken around the rim of exhaust stacks. A small drone could be readily programmed to fly just downwind from a stack and collect gas and particulate samples. Aerial sampling capability for outdoor elevated locations would constitute a new capability that may significantly enhance the ability to inspect for trace products of proliferation.

Figure 1) A small $40 quadcopter that could be modified and used to collect swipe samples from ceilings or walls

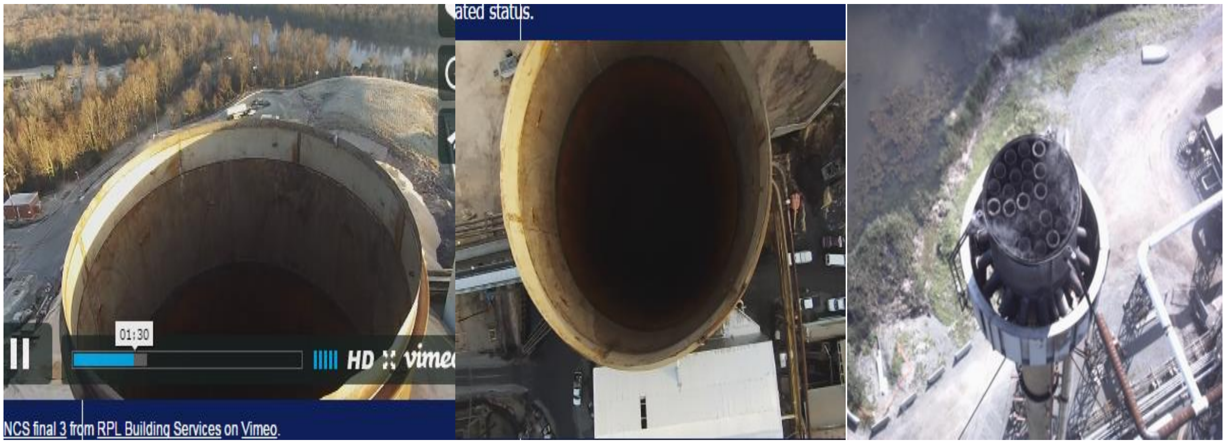

Figure 2) Images captured from commercial drone used for stack inspections. A modified drone could take swipe or atmospheric samples of stack exhaust.

In both indoor and outdoor sampling cases, a complete video record of every sampling operation could be recorded and archived. An autonomous UAV could be programmed to take samples from an area of concern automatically at random or pre-determined intervals. Samples could be securely held for inspectors in a “safe box” and then taken back to fixed laboratories for analysis on a regular schedule.

A sample of commercial inspection systems that are used to perform infrastructure inspections can be viewed at this link: http://rplbldg.net/id78.html

2.2 UAV Deployed – Whole Site - Cameras – “Eye in the Sky”

Use Condition: CA at sites (i.e., locations with facilities or LOFs).

Existing IAEA authority: AP 2a (iii)/6a(visual observation). Or possibly consider this an extension or replacement of satellite imagery.

Fuel Cycle Stage: All

Implementation Priority: High

Technical Readiness: High

Probable IAEA Adoption: Medium

Utilize Richo Theta S, 360 Fly, Nikon Keymission 360 or Nokia Ozo 360 degree cameras mounted on one or more UAVs to provide situational awareness of a location. These 360 degree view cameras could also provide perimeter integrity information to the IAEA, creating a virtual perimeter where ingress and egress would be detected and recorded with visual imagery.

Regular low level flights made with quadcopters around a perimeter fence could record physical structural images that could automatically be processed through change detection software. Facility site changes could be reported with minimal use of staff time. This capability could also provide safeguards “continuity of knowledge” in disaster or perimeter breach scenarios such as at Fukushima. Remotely located inspectors could activate and use UAVs at altitude to record ingress and egress events.

To enable 24/7 operation, one could loft one or more tethered dirigibles over a site, each outfitted with a suite of imaging sensors, radio relay and solar energy harvester designed to allow constant airborne operation independent from ground power sources and safe from tampering or interruption. A 360 degree camera with motion sensing software could be combined with a gimbaled telescopic camera and infrared camera to provide an excellent area-wide traffic monitor and vehicle identification tool. Given the potential payload capacity of a dirigible, this system could also provide the capability to transmit data via radio frequency link and/or satellite link to a central collection point or to a set of authorized users/observers.

UAVs with high resolution 360 degree view cameras could be rapidly deployed to provide real-time image transmission, situational awareness, and safeguards continuity of knowledge if other systems go off-line due to a State or regional wide mains power failure. Archived video and images could provide “witness” to a continuing series of events commonly associated with large facility operations. This evidence could be very helpful in reconstructing/identifying an event of concern.

Continuous images of a whole site would 1) allow the IAEA to reduce the workload of inspectors deployed on the ground – assigned to inspect operations and materials, 2) would intrinsically enhance the depth and scope of knowledge that inspectors could utilize to bolster the probability of detecting proliferation, or diversion activities 3) reduce reliance on satellite images and 4) provide overhead imagery from a more shallow angle providing more of a “side view” of structures, entrances, and vehicles than can be easily obtained with satellite imagery. Although the mix of funding, inspector efforts, and current inspection demands may be adequately balanced, the preparation and deployment of technology to more closely monitor safeguard sites will enhance current results and help to meet future, possibly escalated, inspection requirements.

Figure 3) The Boeing "Scan Eagle" has a flight endurance of over 20 hours and carries advanced stabilized electro-optical and infrared camera. The TCOM aerostat with wide area camera is powered from the ground with a fiber optic cable. http://www.tcomlp.com/?attachment_id=rxjjdicjy. A-NSE offers a variety of surveillance aerostats.

Figure 4) The Fukushima disaster would have benefited from a quick deployment of UAV outfitted with scene recording cameras

Figure 5) UAVs flown around perimeter fences could provide plant inspectors with assurance that physical barriers are intact.

The following links show a sample of commercial 360 degree viewing camera systems that could be mounted to UAVs:1) https://theta360.com/en/ 2) http://www.giroptic.com/ 3) http://www.slashgear.com/bublcam-review-360-degrees-of-spherical-camera-potential-15409285/

2.3 Low Altitude Roaming- UAV Mounted Camera

Use Condition: CA at sites

Existing IAEA Authority: AP 2a(iii)/6a

Fuel Cycle Stage: All

Overall Implementation Priority: High

Technical Readiness: Medium

Probable IAEA Adoption: High if manually controlled by a present inspector. Medium if controlled remotely.

Should a State/Operator try and remove weaponization indicators at a site where the IAEA appear with short notice, an additional layer of defense to illicit activities could be achieved with a small unmanned rotorcraft equipped with a camera that provides real-time imagery to local or remotely located inspectors. Image data would also be captured on high capacity storage devices. In manual mode, the inspector could observe from low elevations locations declared under the AP – just like a ground based inspector – but with a much wider field of view and following a less predictable and less trackable pattern of operation than can be accomplished with ground operations. This UAV capability would give an inspector the ability to quickly change his point of view from one end of a site or location to another – helping to detect illicit movement of objects. Geo-fencing is an electronic means by which small cooperative UAVs can be denied access to certain airspace – regardless of the inspector's attempts to fly into that space. Geo-fences could be applied around buildings and obstacles at any given location to enhance the safety of a manually operated UAV. Geo-fencing would also serve to prevent the UAV from accidently being flown outside a site perimeter.

Figure 6) Left: Geo-fencing can be used to contain UAV operations within agreed upon areas of operation. Right: a small quadcopter could provide inspectors with an easy way to inventory this trailer by providing and overhead view.

Inspectors at local or remote locations could use COTS visual tracking software to task a quadcopter to "escort" vehicles between the entrance gate and their final destination on site – helping to ensure that drivers follow their authorized purpose for site access to maintain continuity of knowledge during infrequent spent fuel material transport to dry storage casks such as CANDU fuel. This could be leveraged for situations where the IAEA does not want to install unattended monitoring systems on transport vehicles.

2.4 UF_6 Container Counting/Cataloging

Use Condition: Inspection or CA at sites

Existing IAEA Authority: CSA and AP 2a(iii)/6a

Fuel Cycle Stage: Conversion / Enrichment / Fuel Fabrication

Overall Implementation Priority: High

Technical Readiness: Medium

Probable IAEA Adoption: Medium

Either fixed wing or quadcopter type UAVs could be used to count, verify and interrogate UF_6 containers. In the case of outdoor storage lots, a single UAV flying at an elevation of less than 400 hundred feet above ground level could be used to acquire aerial photographs that could be analyzed by machine vision counting software. Regular inventories could be accomplished with this technique with very little effort. A quad-copter could also be used indoors for this same purpose. A quadcopter (or multirotor type UAV) has the capability to fly at low elevations, hover, and maneuver between rows of containers. With a high resolution camera and adequate cylinder spacing, a quad copter could rapidly image identification labels on every container in a storage yard. Using machine vision software to identify a label, the autonomous system could apply optical character recognition to read and record identity markings. A combination of database and change detection software could be applied to compare inspections results with previous records – alerting an inspector to changes. A video and image record would be available to inspectors for manual comparison of images flagged by the automated analysis.

Figure 7) Examples of outdoor UF_6 container storage

Examples of commercial counting software that could be applied to UAV collected imagery:

http://countingsoftware.biz/

http://machinevisionsoftware.com/

This UAV enabled inspection and inventory concept can be even further enhanced with additional sensors that are within the payload capacity of small unmanned rotorcraft. For example, a UAV could carry a barcode reader to further identify object ID labels. With the addition of a special lens and software, images collected by the UAV could be analyzed for microscopic flaws (intrinsic identity) that would provide yet another unique (and difficult to fake) identification. Finally, an unmanned rotorcraft could carry a small radiation detector capable of determining information about the contents of the container. These advances would increase the complexity of the equipment, but a skilled integration of mostly COTS (commercial off-the-shelf) technologies is well within our capability today. Such a capability could both replace inspector verification activities and significantly increase effectiveness by being fully unannounced and random at the site placing a much higher risk on a diverter. It is expected that an airborne robotic inventory system would perform inspections and record data several times faster than the best human efforts could achieve. So each inspection effort could include many more containers, and possibly all containers – every time. With a robotic inspection assistant, there may be no need to limit inspections to just a few randomly selected containers. The ability to achieve better coverage during an inspection will enhance statistical sampling and proportionally reduce risk. A UAV system that inspects all containers autonomously on a daily basis essentially becomes a mobile unattended monitoring system that would build significant confidence in material inventory.

2.5 Facility Design Information Verification and Building Contents

Use Condition: Inspection and CA

Existing IAEA authority: CSA Design Information Verification (DIV) and AP 2a(iii) / 6a

Fuel Cycle Stage: All Facilities

Overall Implementation Priority: High

Technical Readiness: Medium

Probable IAEA Adoption: Medium

During DIVs and CAs, IAEA inspector activities are typically limited to floor based assessments with tools like, cameras, laser rangefinders, 3D laser rangefinders, and ground penetrating radar. But many facilities have equipment and physical rooms that have a significant vertical dimension that is not easily explored and documented by inspectors. Small unmanned quadcopters with high resolution cameras could be operated in these rooms and used to acquire images at elevation. Inspectors could use these images to compare the facility against the operator declarations and design information.

With more advanced set-up at each site, UAVs could be programmed to fly autonomously to map in the exterior and interior of a building at regular preset intervals. Flight to elevation allows the LIDAR ("Light Detection And Ranging") scanner to observe infrastructure from angles and viewpoints not easily obtained by inspectors. A complete video record processed with appropriate software could provide a validated floor plan of a facility with all important features and dimensions included. A change detection software package would compare the design and mapped information and then provide a report of discrepancies. Design verification could be more frequently checked during both facility construction and after operations begin.

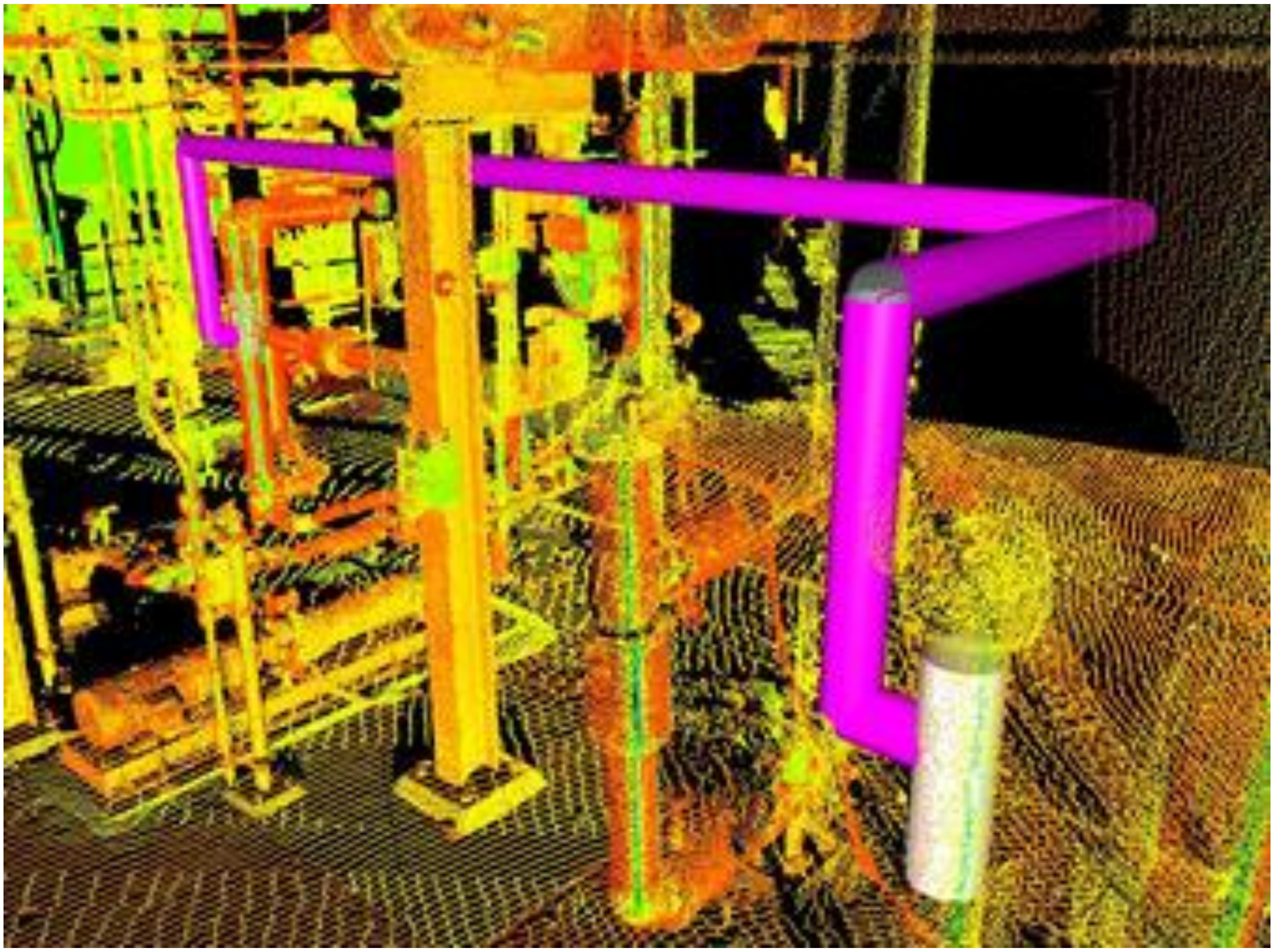

Figure 8) What a reported discrepancy from accepted design may look like after UAV imagery has been analyzed.

Commercially available scanners and software that could be incorporated in a UAV DIV instrumentation suite:

http://truepointscanning.com/3D_Laser_Scanning_Services/Construction_Laser_Scanning.html

http://velodynelidar.com/docs/news/Nuclear%20Inspections%20Made%20Portable%20With%20LiDAR.pdf

https://www.sick.com/de/en/product-portfolio/detection-and-ranging-solutions/3d-laser-scanners/c/g282752

2.6 Spent Fuel Visual Inspection

Use Condition: Inspection

Existing IAEA authority: CSA

Fuel Cycle Stage: Spent Fuel Storage

Overall Implementation Priority: High

Technical Readiness: Medium

Probable IAEA Adoption: Medium

Indoor unmanned quadcopters could utilize high resolution cameras and change detection software to survey, catalog, and find changes among spent fuel assemblies in storage. Flights over storage ponds could be directed to perform random item counting, or to systematically scan and register every assembly. Advantages might include speed and availability to perform regular inventories, the ability to achieve better angles of view – showing all viewable sides of an assembly, and the option to achieve closer proximity to each item for better imaging. This mission could also be accomplished with an unmanned surface or an unmanned underwater vehicle, both of which would afford certain advantages over an airborne system. Such an automated system could replace inspector presence. This is another example of a mobile unattended monitoring/surveillance system that can collect detailed assembly by assembly information.

See news article on poor spent fuel accountability that shows how easily fuel rods can be misplaced or left unaccounted: http://www.hstoday.us/columns/the-kimery-report/blog/gao-finds-nuclear-power-plants-accounting-of-spent-nuclear-fuel-deficient-poorly-regulated/a88c9beba138e74564901d06f0b575ff.html

Figure 9) Top: Images show a variety of spent nuclear fuel configurations that could be monitored with the aid of unmanned robotics. Bottom Left: Small waterproof quadcopters could be flown over spent fuel pools. Bottom Middle and Right: examples of underwater and surface vehicles that would be capable of safely imaging assemblies.

2.7 Yellowcake Barrel Counting/Cataloging

Use Condition: CA

Existing IAEA Authority: AP 2a(v) and 2a(vi) / 6b

Fuel Cycle Stage: Mill – Conversion; storage indoors and outdoors

Overall Implementation Priority: Medium

Technical Readiness: High

Probable IAEA Adoption: Medium

This application would utilize UAVs to count and verify barrels of yellowcake. Working either indoors or outdoors, UAVs can assist manual counts, or work autonomously to count and catalog all barrels of yellowcake at a facility. A quadcopter UAV outfitted with a high definition camera would be a labor saving tool that could autonomously record the position and identification labels on every viewable drum in a storage facility. A video and data record would be archived to provide evidence of a complete inventory. Machine vision software that is commercially available could be employed to analyze the collected video and still images. Precise drum position and label details (including machine vision optical character recognized data) could be summarized in a report – with any changes or deviations highlighted.

Figure 10) Top Left: Yellow cake in steel drums and waste in plastic barrels; Top Right: Tuweitha, Iraq – barrels in poor condition – supposedly empty; Bottom: Drums of yellowcake stored in southern Libya (Credit – The Tripoli Post)

2.8 Repositionable UAV Mounted Camera

Use Condition: CA at sites

Existing IAEA Authority: AP 2a(iii)/6a.

Fuel Cycle Stage: All

Overall Implementation Priority: Med

Technical Readiness: Low

Probable IAEA Adoption: Medium

Autonomous operations are an option for a repositionable UAV camera platform. Envisioned as one or more small quadcopters, these autonomous vehicles would be programmed to "perch" on the top or side of selected buildings and structures and acquire video of operations and areas of interest. Multiple "perch locations" would provide a number of potential camera angles and viewpoints. Software that triggers on movement would instruct the UAV to hold its position when activity is present. When movement has subsided, or at a random interval, the UAV would autonomously fly to another location, perch, and repeat its surveillance activity. This mode of operation would allow near- continuous image collection, interrupted only by occasional excursions to a re-charge station; which itself may be a vantage point for continued surveillance. UAVs could also be teamed to assure that one or more vehicles are active and providing continuous coverage while other vehicles re-charge.

Figure 11) Many research organizations have shown how to "perch" a quadcopter onto a wall or ceiling. This image from the University of Pennsylvania demonstrates a perching maneuver that allows the quadcopter to stick to a wall.

Such repositionable UAV cameras present a potentially unique solution to a difficult safeguards challenge at GCEP facilities. The challenge of concern is the use of undeclared feed whose entry into and out of the facility bypasses the feed/withdrawal stations working directly from the cascades. Having a repositionable UAV camera that can randomly monitor egress points in a cascade building would place the operator at risk of detection if UF_6 cylinders are moved through those egress points.

2.9 Uranium Mine and Mill Production Assessment

Use Condition: CA

Existing IAEA Authority: AP 2a(v) and 2a(vi)/6b (visual observation)

Fuel Cycle Stage: Mining, Extraction & Refining

Overall Implementation Priority: Low

Technical Readiness: High

Probable IAEA Adoption: Medium

Utilize UAVs to collect imagery and 3-D terrain volumetric data to map uranium mines and operations, and sample ore that produce yellowcake and mill tailings. Depending on the type of sensors employed, the UAV could operate during the day or night. UAVs can work autonomously to completely map an entire above ground mining operation. They can simultaneously record video of the operation and with associated software can provide a summary report including volumetric and structural changes since the last mapping. Utilizing a UAV, this data could be updated very frequently at a cost far below costs associated with manned flight platforms.

The major advantage of UAV collected imagery in comparison to satellite imagery is that images from the UAV can provide much higher resolution; which is necessary for meaningful volumetric analysis. Although commercially available satellite imagery is not too expensive (~$50.00 to $200 per image depending on quality), it can only provide a native resolution of about 50 cm. Whereas a 12 megapixel camera mounted to a UAV flying at 100 feet above ground level will provide better than 2cm resolution. In addition, the UAV mounted camera can supply an almost unlimited number of images that can be acquired from a variety of different angles; providing inspectors with an information rich data set.

UAVs can also be used to volumetrically map underground mine shafts. Using LIDAR, mid-sized quadcopters have been flown to map mine shafts and determine excavated volume.

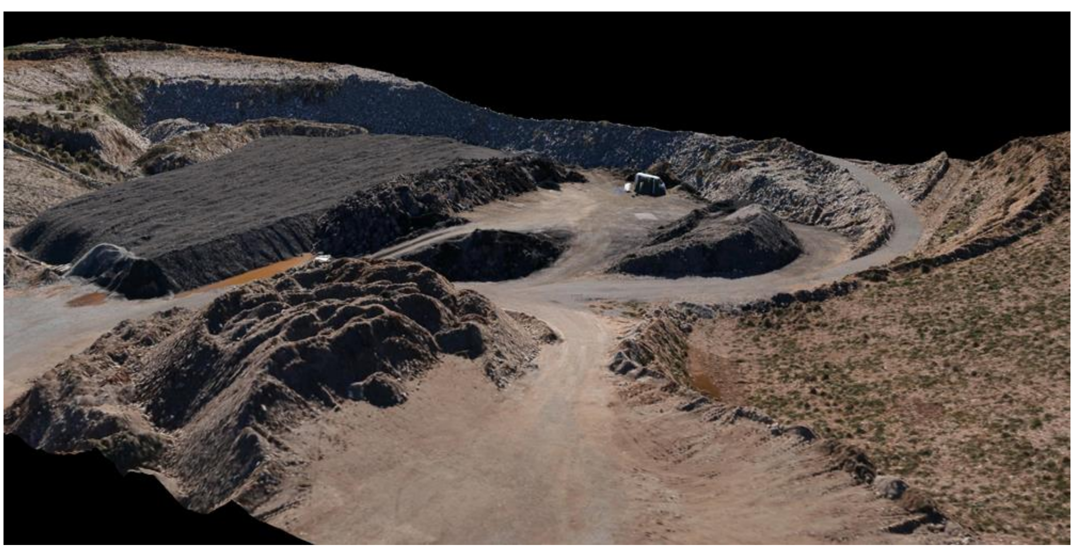

Figure 12) Digital Terrain Model by "Altitudefilmworks.com"

Volumetric map data and ore sampling supplied by a UAV could be used by analysts to better understand production by watching mining patterns and rates of ore removal. Volumetric maps can also be used to find mines that have not been declared, or have not yet been found. Through observation of ground vehicle traffic patterns collected via airborne imagery, combined with volumetric analysis of ore piles, analysts may be able to determine if material is being distributed to undeclared users, or shipped to undeclared locations. Analysts should be able to reconcile mine volume with ore piles, tail piles, and shipments.

Uranium mill operations like the COGEMA Resources Inc.'s McClean Lake in Canada and Bois Noirs site near Loire, France, utilize a subaqueous disposal process. (See a report on the COGEMA site at: http://www.wmsym.org/archives/1998/html/sess29/29-02/29-02.htm; and the Bois Noirs site at http://www.sciencedirect.com/science/article/pii/S1878522013001896) It may be possible to utilize unmanned underwater vehicles (UUVs) equipped with side scan sonar to create the same type of volumetric maps as those commonly created with airborne systems today.

A sample of potentially useful commercial products can be viewed at the following links:

http://www.identifiedtech.com/products/

http://www.menci.com/3d-modeling-software/terraintools

https://www.sensefly.com/applications/mining.html

http://www.airborne-robotics.com/en/application/aerial-surveying-and-measurement

http://www.microaerialprojects.com/services/mining-volumetrics/

http://clickmox.com/products/minefly/

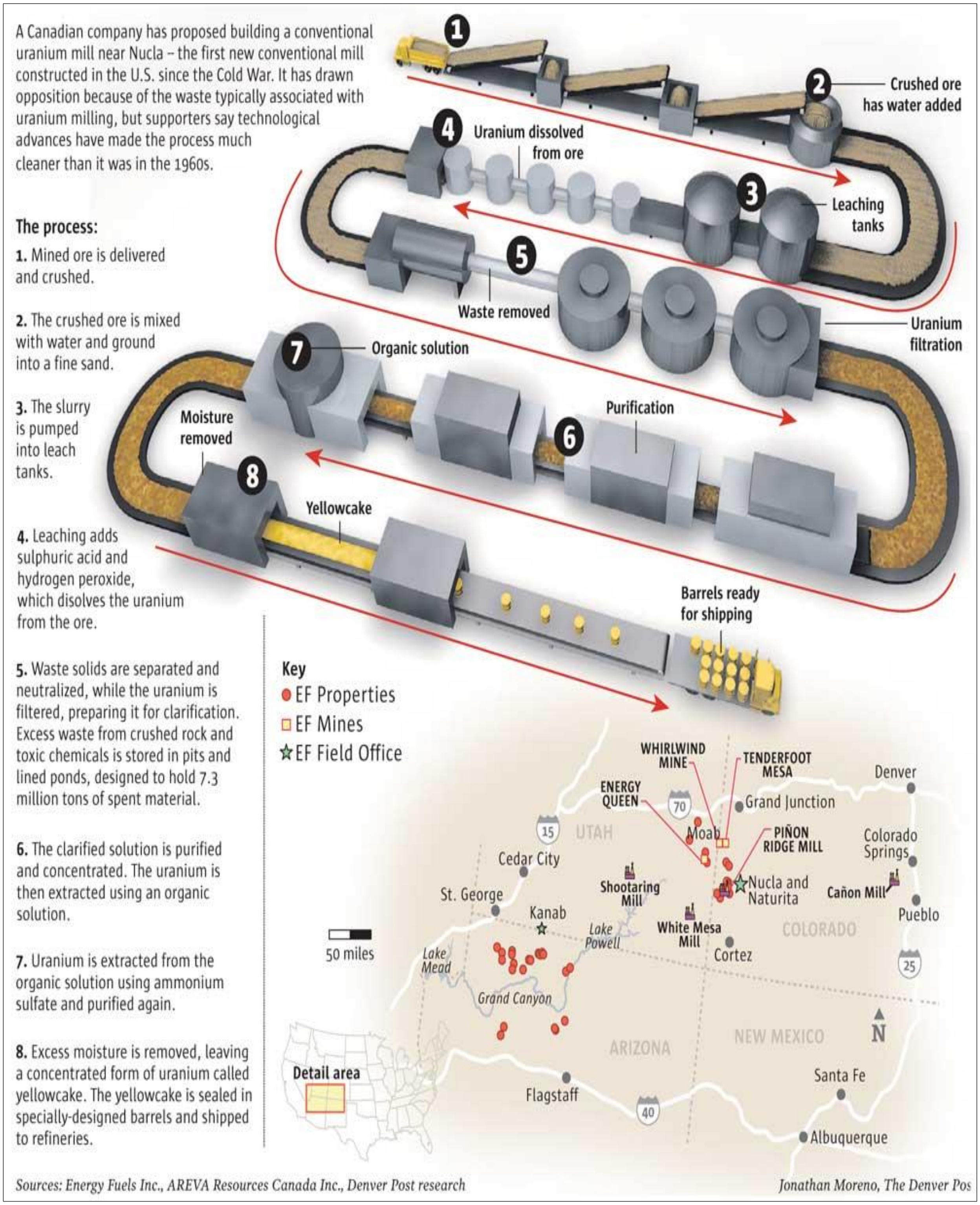

Figure 13) Uranium Ore Processing (the Denver Post http://www.denverpost.com/ci_13647439)

2.10 Nuclear Waste Repository Mapping and Change Detection

Use Condition: Inspection and CA

Existing IAEA authority: CSA. AP 2a(iii)/6a

Fuel Cycle / Stage: Waste Storage Facility

Overall Implementation Priority: Low

Technical Readiness: Medium

Probable IAEA Adoption: High

UAVs could be used in conjunction with LIDAR, stereo vision imagers or high definition cameras to volumetrically map a repository; and on subsequent visits detect changes. The UAV would fly through the repository and make a complete volumetric map of the facility and any exposed storage containers. On subsequent visits the UAV would collect the same map data then compare the software analyzed data for changes. An automatically generated report would summarize any changes in object positions or count.

Once a complete inventory is established at a facility, a UAV mounted camera system similar to topic 2.3 in this report could be deployed at the facility entrance. Programmed to automatically deploy and visually inspect each transport going into and out of the entrance point, a UAV deployed camera would record contents of flatbed trailers. Inspectors would be able to maintain an accurate accounting of casks and containers by reviewing the telemetered images – even if they are based at a distant offsite location.

Figure 14) Waste Containers – Left: WIPP - Carlsbad, NM: Using a notional "quadcopter and a small camera suspended by a string," an inspector may be able to confirm the identity of material that is closely stacked as in the top left image. Middle and Right: storage arrangements that could be quickly surveyed with a small quadcopter.

In the case where the repository is sealed, UAVs could be used to survey the area to assure that there are no other penetrations into the area to gain access to the material within.

2.11 Corrosive Process Sampling with Chemical Resistant Unmanned Airborne Access Vehicle

Use Condition: Inspection

Existing IAEA authority: CSA at key measurement points

Fuel Cycle Stage: Open chemical process/storage/waste vats/ponds

Overall Implementation Priority: Low

Technical Readiness: Medium

Probable IAEA Adoption: Medium

A quadcopter type device could fly over radioactive or hazardous areas; including liquid surfaces that an operator might not be able to access. With a small sampling device slung beneath the quadcopter, the vehicle could retrieve a liquid sample. Current efforts by researchers have produced quadcopters that are liquid proof and highly resistant to acid and caustic environments. The vehicle would be designed and certified to withstand contact with the hazardous solution, and sealed in a Teflon or polymer skin that would prevent adverse reaction if the vehicle were to become accidently submerged in the solution. Efforts to achieve this type of corrosion resistance have begun with systems like the "CRACONS" at Johns Hopkins Lab (http://www.jhuapl.edu/newscenter/pressreleases/2016/160317.asp). Examples of water sampling and waterproof quadcopters are shown in the figures below.

Figure 15) A water sampling aerial robot is being developed by the University of Nebraska, Lincoln – along with University of California Berkley - with funding from the U.S. Department of Agriculture.

Figure 16) Oakland University "Loon" drone can endure stints of underwater operation, then rise to the surface and become airborne again. https://www.youtube.com/watch?v=K_wiVdY5BWU

3.0 A small set of Use Cases that involve other types of robotics

There are, perhaps, many dozens of other applications for unmanned systems in the safeguards arena that would involve non-airborne devices. Applications from underwater monitoring to the use of self-driving vehicles can be imagined. Although this paper has been limited primarily to unmanned airborne vehicles, the next three applications are submitted to show a small part of the potentially expansive scope that unmanned systems could play in future safeguards efforts. PNNL would welcome further inquiries to consider the use of other types of robotic mechanisms and vehicles.

3.1 Duct Bot

Powered by air duct "wind," this robot would roam ventilation ducting; taking samples and radiation readings. The robot would trigger on anomalous readings and take samples continuously or when interesting results are indicated. Samples of airborne particulate could be collected on a continuously advanced spool of filter material and preserved for future analysis. This type of sample archival could provide inspectors with knowledge of the timeframe when a proliferation activity was carried out. The robot would return to a retrieval station when summonsed by authorized operators. This type of "robot" might also just be a static fixture on a return air vent in a facility or room or interest. This device could supplement current efforts to inspect facilities where swipe samples are collected from surfaces. As a continuously operating air monitor, a sample of airborne particles would be collected before they deposit on surfaces. The potential application might be during decommissioning and deployed as a Joint-Use system shared with the operator.

3.2 Manually Deployed Machine Vision Applications

Inspectors tasked with inventory reconciliation tasks that require them to count objects or record identification numbers and compare the results against the operator's general ledger or list of inventory items could be provided with imaging systems linked to computers with machine vision and optical character recognition software. Count and identification data could be automatically acquired and recorded with essentially 100% accuracy. The time savings would be significant.

Figure 17) Items like these fuel pins can be counted with machine vision imager to rapidly complete the task and obtain 100% accuracy.

18) Seals could be verified in the field by their unique surface characteristics using high definition imagery, and change detection software that compares an inspection image with previous data.

3.3 Self-Driving Perimeter Inspector

Most nuclear safeguard facilities feature a perimeter fence and road. A self driving vehicle could be employed 24/7 by inspectors to maintain awareness of ingress and egress – including visual records of construction vehicles and payload. A self driving vehicle might also be programmed to position itself and park at locations downwind from the facility at any given hour. Onboard sampling equipment would have the best chance for collecting atmospheric particulate or gasses associated with undeclared activities. The self-driving vehicle would, perhaps, represent a significant equipment and deployment savings – as it would replace the need to deploy several stationary sampling stations – and would simultaneously provide more effective and assured collections – as it would always be located downwind from the site of interest.

6) Self Driving Vehicles come in hundreds of configurations – capable of blending in to a variety of use scenarios.

4.0 Conclusion

The future of inspection, monitoring, data and sample collection will be heavily influenced by semi-autonomous and fully autonomous robotic assistance. Unmanned robotics provides a culmination of physical, detection, and recording capability that cannot be easily matched by individual human effort. Unmanned systems represent untold hours of human expertise concentrated into tools designed to perform specific tasks and assist with human endeavors. Today, unmanned systems have become more robust and reliable. However, the implementation of unmanned robotics is still just beyond its infancy. Certain efforts must be accomplished to prepare an unmanned system for duties beyond the simplest imaging and navigation tasks. Although there are commercial, agricultural and military deployments of unmanned systems that perform with reliability and accuracy every day, almost every new deployment requires some degree of "set-up" or customization by human experts.

Deployment of unmanned systems in the safeguards arena will necessitate a certain level of technology and systems integration, and in some cases will require technical development and software customization. Implementation of UAVs for more unique safeguards applications will require a lead organization to build relationships across national assets to form the most coherent and robust systems that take advantage of specific technologies and analytic capabilities currently spread among multiple institutions. Policy and management considerations will also need to be addressed. An investigation into country specific regulations for unmanned systems and building new facets of our state relationships specifically regarding the use of robotics will be important tasks. Training inspectors, developing deployment strategies, implementing stewardship, developing data collection and analytics routines, and executing maintenance programs for unmanned systems will require a coordinated management team tasked to guide this important advancement in safeguards inspections.