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Unmanned Aerial Systems for Safeguards Inspections of Uranium Mines

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ABSTRACT

Unmanned Aerial Systems (UASs) have achieved geometric growth in the commercial market and show promise for many industrial applications. UASs may also present an opportunity to aid in certain safeguards applications, including conducting complementary access inspections for uranium mines and deployment of radiation sensors for remote measurement and telemetry. These systems may be able to help achieve the goals of the nonproliferation regime and the International Atomic Energy Agency (IAEA) by adding capabilities which were formerly either unsafe or technically infeasible. The current generation of UASs face constraints on range, payload, and maneuverability which limit the potential safeguards applications. Two- and three-dimensional imaging, volumetric assessments, radiation dose mapping, and hyperspectral imaging are some of the technical applications which UASs are likely capable of contributing to the safeguarding of mines. The implementation of UASs in safeguards applications of uranium mines presents a number of safety, security, and regulatory/political issues which must be considered and mitigated. However, none of these barriers appear insurmountable. The implementation of best practices in technology and training will ensure that the IAEA, operators, and host nations incur a minimal risk to safety, security and regulatory/political issues. This paper begins by outlining how UASs may help achieve safeguards goals within the specific application space of uranium mining activities. Current limitations are discussed, followed by a brief technical assessment of potential UAS capabilities which would be relevant to mining inspections. Future technology trends in UASs will be discussed on how they may impact the proposed mine inspection mission. Finally, the paper presents a brief overview of related safety, security, and regulatory/political issues which must be considered.

LEGAL FRAMEWORK FOR SAFEGUARDING URANIUM MINING AND URANIUM/THORIUM CONCENTRATION ACTIVITIES

Under Comprehensive Safeguards Agreement INFCIRC/153, uranium mining and uranium/thorium concentration activities are not required to be reported. However, the State must declare the quantity, composition, and destination of the uranium or thorium if it is exported for nuclear purposes to a non-nuclear weapons State.[1] If a State is a signatory of the Model Protocol Additional to the Agreement(s) between State(s) and the International Atomic Energy Agency (IAEA) for the Application of Safeguards (INFCIRC/540), or simply the Additional Protocol (AP), Article 2.a.(v) requires the signatory State to inform the IAEA of the location, status, and annual production capacity of its uranium mines and concentration plants, as well as its thorium concentration plants.[2] It also requires the State to inform the IAEA of the total estimated production capacity of its mines and concentration plants. However, the State does not have to conduct detailed nuclear material accountancy on these

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values. A State must declare information regarding exports to non-nuclear weapons States and imports of uranium in excess of ten tons per year and thorium in excess of twenty tons per year, including quantity, composition, origin, destination, date of shipment, and receipt.[3] The AP also grants IAEA inspectors the right for complementary access to ensure the absence of undeclared nuclear material, to ensure the correctness and completeness of a State's declarations, or to verify the status of a decommissioned facility.[4] Inspectors are granted access to both the mine and the mill.

The IAEA currently uses satellite technology to assist with identifying the location, operational status, and estimated capacities of uranium mines.[5] This also includes satellite hyperspectral imaging to analyze drilling, mining, and milling activities.[6] However, the AP does not grant the IAEA authority to mechanistically or systematically verify the activities and material declared at uranium mines and milling facilities. Furthermore, doing so would prove prohibitively costly relative to the safeguards benefit it would return. With this in mind, the propositions of this paper will be more related to a general assessment of activities. Some researchers doubt the feasibility of being able to detect undeclared mining.[7] These individuals argue that while the AP requires the reporting of mines and some of their basic characteristics, no legal framework exists giving the IAEA the power to apply safeguards or verify the information. Furthermore, they argue the technical requirements are not feasible for three reasons: 1) the measurement uncertainties are too high, 2) the cost for maintaining a controlled area over the entire mining site is prohibitively high, and 3) it is impossible to verify that uranium byproduct of undeclared non-uranium in situ leach mines is not being diverted.

Safeguards reporting to the IAEA regarding a State's uranium mining and concentration activities contains limited but crucial information to enforce the nonproliferation regime.[8] The reporting of uranium mining and concentration activities and imports/exports of uranium ore help ensure the completeness and correctness of a State's declarations. The IAEA will confirm information regarding shipments with the receiver state, and inconsistencies may indicate undeclared activities.

TYPES OF URANIUM MINING ACTIVITIES

The four classifications of uranium mining facilities investigated for potential UAS application are displayed in **Error! Reference source not found.**. In open pit mines, the conventional milling impoundments are limited to 40 acres (0.16 km^2) by the Nuclear Regulatory Commission (NRC).[9] The above-ground facilities of an underground mine include warehouses, equipment facilities for pumps, and stockpile areas.[10] Underground mines typically have areas ranging from just 10 acres to 25 acres (or 0.04 km^2 to 0.10 km^2).[11] While flying UASs underground may be difficult and hazardous, it may be useful in situations where radiation levels are high due to radon or if the mine is unstable. Great strides have been made in vision-based UAS obstacle avoidance[12] that may make this more feasible, but dust may be a limiting factor. Heap leaching sites are typically located near open-pit or underground mines where the low-grade ore is transported via truck to the site. In the U.S., heap leaching piles are limited to 40 acres (0.16 km^2) by the NRC but since one site can have multiple piles, the total area is typically hundreds of acres.[13]

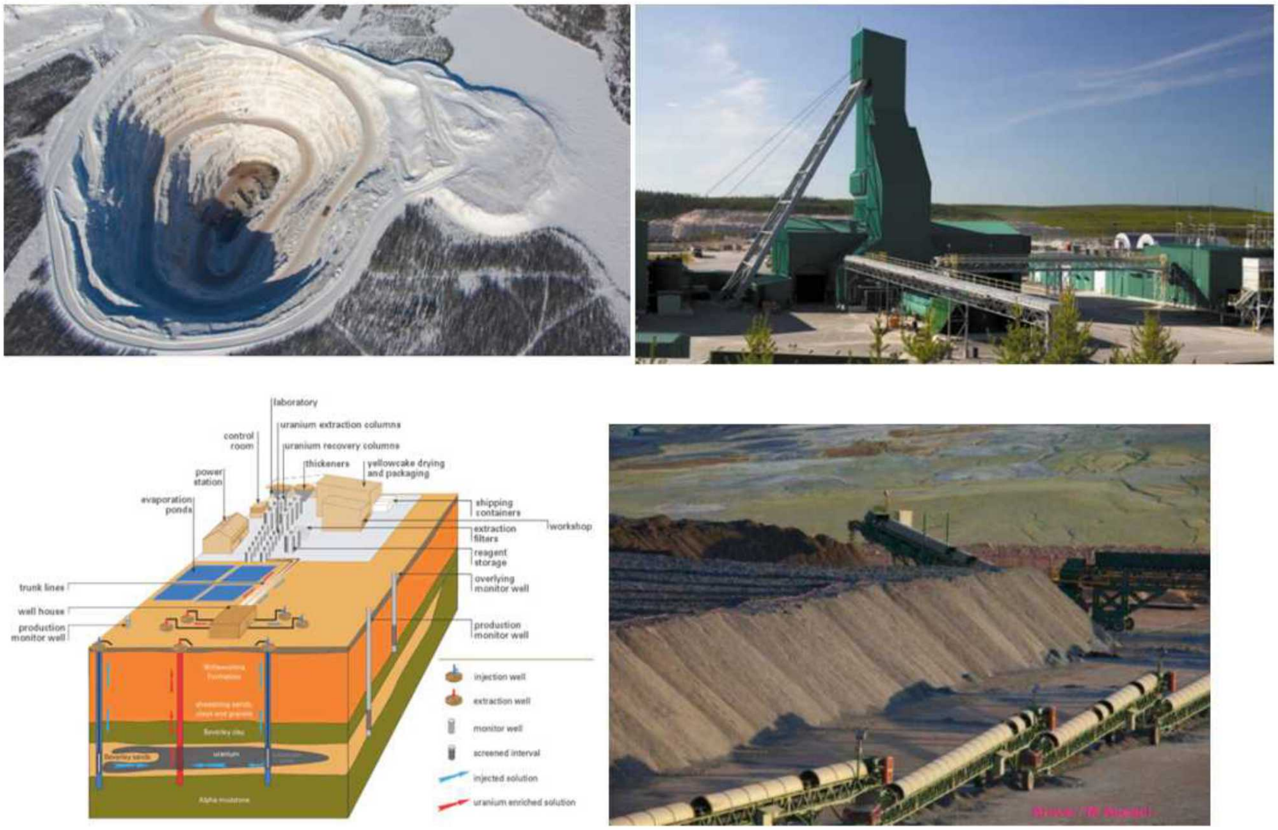

Figure 1: Top-Left: The Canadian McClean Lake open-pit mine.[14] Top-Right: The Canadian McArthur River underground mining facility.[15] Bottom-Left: In situ leach mining process.[16] Bottom-Right: Heap leaching of uranium ore.[17]

FEASIBILITY ANALYSIS

Technical capabilities that could support safeguards activities in those use cases include: volumetric assessments and 3-D imaging, topographic characterization of the radiation dose or count rates, real-time on-board gamma spectroscopic measurements, and 2-D and hyperspectral imaging. In this work we analyze the technical feasibility for each of these capabilities for use in mining safeguards via UAS platforms. Technical feasibility is an assessment of a technology's readiness to be deployed for the specific safeguards application. An analysis of today's current capabilities of UASs will be considered as well as the trajectory and pace of development that is being observed.

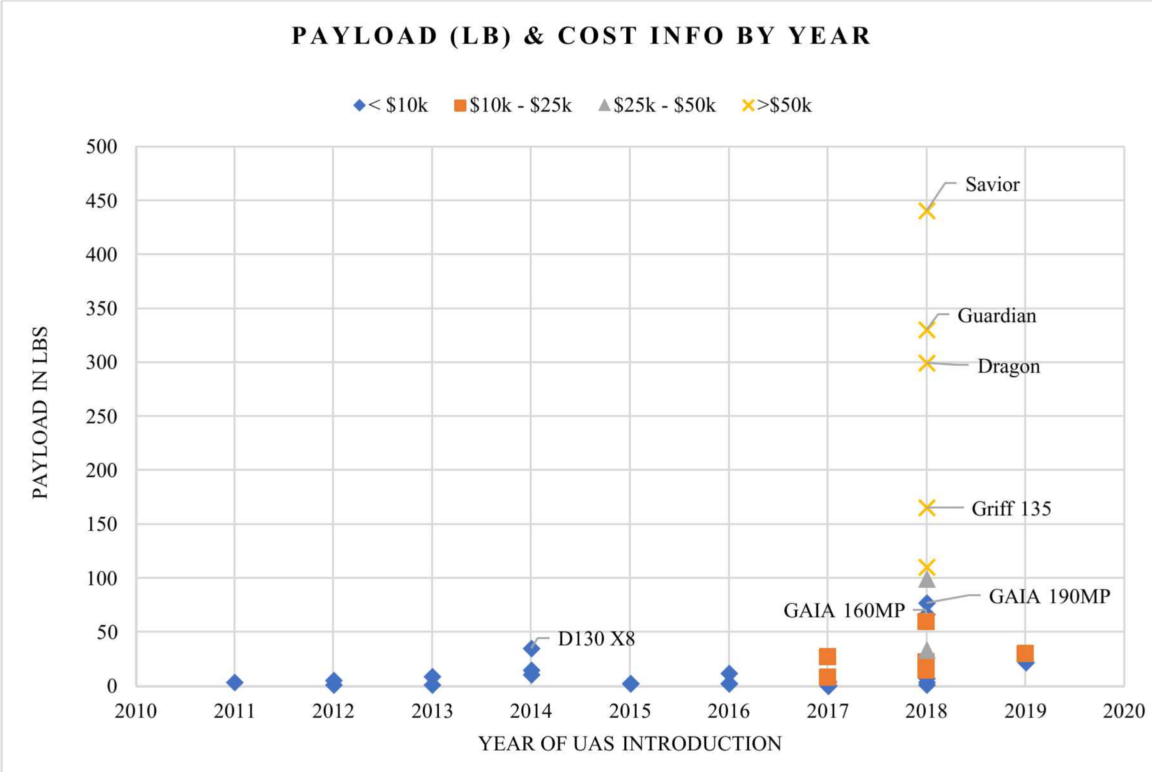

Figure 2: UAS Payload & Cost by year of introduction

Figure 2 shows a graph of the evolution of UAS payload capability differentiated by the year they were introduced on the market and their cost. Note that 2018 was a breakthrough year in the cost vs. payload metric. This shows that there are ample UASs available on the market that can carry significantly heavy payloads, at a cost that is becoming much more competitive. The Foxtech Gaia MP line of UASs is cost-effective ($3,600 to $9,700) with significant payload capabilities from 35 to 60lbs[18]. Hybrid energy gas/electric UAS are available in the $25k-$45k range with flight times in the 4 to 5-hour range with up to 30lb payloads (Foxtech, and Harris Aerial)[19]. This data clearly shows a steady increase in payload capability and an overall decrease in the ratio between cost and payload capability.

UAS Hybrid Power Systems Provide Extended Flight Time and Range

Traditionally, small UAS used gas as their source of power. While this provides a very high energy density, there are difficulties associated with gas and recreating engines. When Direct Current (DC) motors and then Brushless DC (BLDC) motors began to become more reliable and common place, batteries were the choice for the source of power, with Lithium Polymer (LiPO) being the current battery source with the highest energy density. Hybrid technology combines the advantages of two or more power sources to create a more efficient power system. Recently, there have been breakthroughs in small generators and fuel cells which provide the ease of use of electric with the endurance of gas.

<u>Gas/Electric</u>

The hybrid-electric power system is here defined as the combination of an electric motor and an internal combustion engine (ICE) within one power plant. These can be integrated at manufacturing time or added as an aftermarket capability. A heavy-lift payload is required, usually in the 10-15kg range. Hybrid gas/electric systems use about 4kg in the generator and another 4kg in fuel and can add hours of additional flight time over a battery.

Hydrogen Fuel Cells

A hydrogen fuel cell converts chemical energy stored by hydrogen fuel into electricity. Hydrogen on its own is not a source of energy. It must be kept in a suitable container until it is ready to be used in a fuel cell to produce electricity. When hydrogen is combined with oxygen within the fuel cell, and the byproduct water is removed, the fuel cell can generate electricity. The first hydrogen-fueled small UAS entered the market on April 2016. Hydrogen is colorless, odorless, and nontoxic gas that won't produce acid rain, deplete the ozone, or produce harmful emissions. When converted to energy it only has one byproduct: water. Hydrogen fuel cells have a higher energy density over batteries, refuel quickly and function in low temperatures.

In January 2019, a 44-pound multi-rotor Project Rachel UAS powered by an Intelligent Energy hydrogen fuel cells has achieved 70 minutes of continuous flight while carrying an 11-pound payload[20]. This is a substantial improvement over the aircraft's 12-minute endurance when using LiPO batteries. In the same month, MetaVista Inc conducted a record-breaking test flight of nearly 11 hours with a quadcopter using an Intelligent Energy fuel cell module[21].

SENSOR PAYLOADS

Volumetric Assessments and 3-D Imaging

Light detection and ranging (LiDAR) sensors can provide UASs with the capability to create three-dimensional maps of mines. By using pulses of laser light and measuring the distances, LiDAR creates a cloud of points, each with GPS coordinates.[22] Through these point clouds, very precise 3-D topographic models of the earth's surface can be created. Resolutions down to < 1mm are possible.[23] This information can then be used to estimate the total volume of uranium produced. 2-D satellite imaging does not provide the information necessary to make volume estimates. Potential applications of LiDAR on UASs for mining safeguards include:

- Open-Pit Mine: 3-D imaging of a portion of the mine, contouring, and volumetric assessments of stocks of material. LIDAR differencing between 3-D images collected from subsequent flights over a mine can determine if large quantities of ore have been removed from the surface[24]. If a large pile of material was present during the first flight and the missing in subsequent flights, the inspectors would be able to flag measurable changes.
- Underground Mine: Milling and processing facilities for underground mining may be sufficiently small to allow unmanned ground vehicles (UGVs) to collect 3-D images of the site layout, roads, and major equipment. LIDAR Scanning is another option in this scenario as well[25].
- In Situ Leach (ISL) Mine: Milling and processing facilities for ISL mining may be sufficiently small to allow UASs to collect composite 3-D images of the site layout, roads, and major equipment. However, the size of the wellfield can range into the thousands of acres, making this entire area difficult to survey.
- Heap Leach Mine: UASs may assist with 3-D imaging of a portion of the mine, contouring, and volumetric assessments, as well as changes from subsequent visits.

The IAEA currently does not conduct nuclear material accountancy or 3-D imaging of mines. Commercially-available 3-D imaging and volumetric sensing technologies exist which are capable of conducting 3-D surveys of sites with great speed and precision. Some companies claim that what previously may have taken a day to accomplish through taking elevation measurements every 5 to 10 feet for mapping a 30-acre site can now be accomplished in approximately 30 minutes.[26]

Figure 3: StormBee 3D scanning UAS

The Belgian company, Think 3D, integrates their StormBee UAS (shown left in Figure 3) with the long-range (130m), high-accuracy (+/- 2-3 mm) FAROx130 LIDAR[27]. This system is well suited to open pit mine scanning, capable of covering a 53,000m^2 scanning area within the flight time of one battery charge. Approximately 8 flights with this scanner would be needed to cover the 0.42 km^2 [28] of the Areva mine planned in Niger. This is a significant capability that bears further analysis for this application space.

The eBee by senseFly UAS is integrated with mapping systems.[29] The mapping data can then be translated into a 3-D model, but the operator must export the data to their own processing software. However, an optional add-on, Pix4Dmapper, can generate orthomosaics in addition to 3-D digital surface models and point clouds.[30]

The trade-space between different measurement and UAS technologies is determined by the requirements of the monitoring regime. For gross levels of differencing, a small, fixed-wing photogrammetry UAS may offer enough 3-D accuracy to provide useful information in a timelier manner. For more accurate volumetric estimates, a scanning or flash LIDAR mounted on a multirotor UAS may be required.

Radiation Detection

Radioactive isotopes emit radiation which can be measured and characterized with radiation detection equipment. There are two potential applications of radiation detection which may be conducted with UASs for mining applications.

Topographic Mapping of Radiation Dose On Site

It is possible to equip a UAS with dosimetry equipment to characterize the dose rate at locations on the surface of a mine. For underground mines with large levels of alpha radiation from radon gas, UASs may be useful to prevent unnecessary worker exposure. Furthermore, if radiation levels in certain areas of a mine are suspiciously high, these sites can be labeled for later sampling by IAEA inspectors to verify the absence of undeclared nuclear material or activities. Topographic radiation dose characterization would be most readily accomplished via count rates obtained on Geiger-Müller tubes, scintillation detectors, or lower-cost semiconductor detectors such as cadmium zinc telluride (CZT). Neutron detection would be infeasible due to the operational height of the UAS and the low neutron emission rates of ^{235}U and ^{238}U.

There is significant proof-of-concept for the characterization of radiation fields using UASs. At a contaminated site near the Fukushima Daiichi Nuclear Power Plant, a multi-rotor UAS equipped with a laser rangefinder and a CZT semiconductor gamma-ray spectrometer was used to impose radiation measurements onto a topographic map in close to real-time.[31] The area surveyed over the 15-minute flight was extremely small, measuring 0.01 km^2. For comparison, the largest planned open-pit mine is planned by Areva in Niger and will be 0.42 km^2.[32] Imaging this mine at the same rate as in the previous study would require over 10 hours. However, as obstacle avoidance and flight times improve, it may be possible for the UAS to get much closer to the surfaces being measured, allowing for shorter dwell times which increases the speed of the survey and the total area covered.

Real-Time On-Board Gamma Spectroscopic Measurements

The determination of the energy and intensity of gamma rays emitting from a substance can be used to identify the type and concentration of isotopes in the material. It appears that current radiation detection on-site for mines is conducted with hand-held spectroscopic equipment. An image in a publication from the Australian Safeguards and Non-Proliferation Office displays an inspector using what appears to be an identiFINDER R400 on a pipe at an in situ leach mine.[33]

Figure 4: Identifinder R400 Spectroscopc Analyzer

The accomplishment of this measurement in real-time on board UASs has been a demonstrated technology which could improve the ability of inspectors at any type of mine to verify the absence of undeclared nuclear material or activities. This may also be useful for mining applications where the ore being shipped out or samples obtained can be characterized by its radioactive isotopes. One experiment demonstrated the use of a multi-rotor UAS equipped with a CZT semi-conductor detector to obtain gamma ray spectra from natural uranium-containing granite samples.[34] The GPS and spectral data was transmitted in real time. The system is capable of a 12-minute flight time and a maximum survey area of 100 m^2. Despite the low flight time, the system was capable of identifying radioisotopes including ^{230}Th, ^{234}Th, and ^{235}U from low-radioactivity samples with an 800 s count time at a height below 3 m.

A study to detect ground-level radioactivity on board a fixed-wing UAS demonstrated the difficulty in reduced dwell times.[35] The ^{137}Cs and ^{60}Co source activities in this study are extremely high relative to that which would be likely be present in uranium mining and uranium/thorium concentration activities. Therefore, this application would be most useful for verifying the absence of highly-radioactive material, but mining applications will likely require the versatility of a multi-rotor UAS.

2-D Hyperspectral and Visible Imaging

UASs can be equipped with cameras for real-time transmission of photographic or video data to the user. This can be used for overall characterization of any type of mining site to allow IAEA inspectors on the ground to verify the presence of buildings and extent of the site. For subsequent inspections, this information can also be used by the IAEA to verify if new equipment or buildings are present, or if stocks of material have been moved. UASs have the advantage over satellites of being able to image with less atmospheric interference. This information can also be provided at a faster rate than current satellite 2-D imaging. High-resolution imaging capable of being integrated with UASs is readily available in commercial off-the-shelf technology.

Hyperspectral imaging can assist in verifying the composition of the materials at the site of the mine and may also assist in identifying locations where IAEA inspectors should collect samples. This device works through measuring varying wavelengths of light emitting from small sections of the surface of the earth and piecing the information from those sections together into a representative image of the entire site. Individual minerals have unique vibration and electronic properties which can be distinguished through this methodology.[36] Integration of hyperspectral imaging on UASs may assist in verifying the exposed ore at open pit or heap leach mines. This technology may also be used to estimate production capacity through imaging of tailings ponds.

An important consideration of hyperspectral imaging is the required resolution to distinguish the characteristic absorption bands of a particular element. Atmospheric conditions can interfere with this. Satellites are currently capable of conducting this type of imaging, however UASs would not be subject to as much atmospheric interference. An additional potential barrier specific to uranium is that the concentration of uranium in deposit samples at mines may not meet the minimum detectable quantity for hyperspectral imaging. However, if present, Mg-calcretes have been displayed to be an adequate, measurable proxy to map uranium concentrations using satellite-based and laboratory hyperspectral imaging.[37]

CONCERNS

The implementation of UAS technology into uranium mining and uranium/thorium concentration safeguards applications presents a number of significant safety, security, and regulatory/political barriers which must be addressed and mitigated. These concerns will be expressed by IAEA inspectors, facility operators, State officials, and facility safety and security officers. This section seeks to identify those concerns and weaknesses in each of the three areas of safety, security, and regulation/policy, and makes several recommendations to mitigate these concerns.

Safety

For underground mines, UASs would face navigation challenges when attempting to operate in a dusty indoor environment. Experiments at Sandia Labs with small UAS flying inside dusty, enclosed spaces demonstrated that dust propelled by the UAS props under thrust could interfere with first person video and navigational sensors to the point of failure. This renders much of this application space useless. This compounds safety concerns when that dust is radioactive. Fortunately, most uranium mines and concentration facilities are outdoors, mitigating this concern. If needed, indoor measurements may be more effectively and safely accomplished with UGVs and/or human inspectors.

Security

For a detailed analysis of how UASs may impact the security of nuclear facilities, see Solodov et al., (2017).[38] For physical protection of uranium mines, the Convention on the Physical Protection of Nuclear Material (CPPNM) mandates that yellowcake is “protected in accordance with prudent management practices.”[39] Uranium mining and uranium/thorium concentration activities do not carry significant sensitive information which would be a security or proliferation concern. Furthermore, the UAS and computer networks will have encryption which acts as a security barrier commensurate to the threat posed and the sensitivity of the information.

Regulatory/Political

Many States have their own rules and federal regulations for UAS use.[40] Safety regulations vary based on characteristics such as weight, operational altitude, payload, and purpose. There exists no comprehensive international framework for UAS regulations. These rules and regulations must be consolidated if IAEA, State, facility, or other third-party personnel are to operate under a consistent framework during inspections, and to mitigate the possibility of disagreements. A starting point may be the UAS Regulations & Policies from the Federal Aviation Administration (FAA).[41] If no international agreed-upon framework can be reached, inspectors must comply with the State and site-specific rules and procedures of the facility being inspected. However, this may require inspectors to have licenses in multiple countries, making the process complicated and difficult to maintain.

CONCLUSIONS

Mining and concentration activities present a unique opportunity for the integration of UASs for safeguards applications. It appears that the most promising safeguards applications of UASs for near-term implementation are volumetric assessments with 3-D LiDAR and 2-D imaging. Particularly for mines, these two technologies can survey a large area in a short inspection time while allowing inspectors to collect more precise data than previously possible. Hyperspectral imaging with UASs, while promising, faces several technical limitations such as resolution which must be further investigated to determine its effectiveness. Radiation detection with UASs does not appear to be particularly useful for mining applications due to the low radioactivity of material present at mines. Implementation of UASs in mining and concentration activities will not introduce significant safety or security issues since mines do not contain sensitive information or fragile equipment.

As UAS technology continues to proliferate and the individual systems become more advanced, the number of industrial and commercial applications will grow, and payload capability and flight time will continue to rise. Large mines may have areas in the range of hundreds to thousands of acres. Hybrid power aircraft may provide the capability to address sites that large. These systems are currently sufficiently-small to have minimal effect on operating time. Alternative technologies, including hand-held sensors and satellite imaging, must be constantly compared with UASs to assess the benefits and risks of each.

REFERENCES

[1] International Atomic Energy Agency, "The Structure and Content of Agreements Between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons," Austria (1972), para. 34 (a)
[2] International Atomic Energy Agency, "IAEA Safeguards Glossary," 2001 Edition, Vienna (2002), p. 40.
[3] Akos Petoe, "Safeguards Obligations related to Uranium/Thorium Mining and Processing," International Atomic Energy Agency, Vienna, URAM 2009, http://www-pub.iaea.org/mtcd/meetings/PDFplus/2009/cn175/URAM2009/Session%201/4_114_Petoe_IAEA.pdf.
[4] "IAEA Safeguards Glossary," p. 91.
[5] Johnson Michael Richard, Paquette Jean-Pierre, and Elbez Julien, "New And Emerging Trends In Satellite Imagery," *2014 Safeguards Symposium*,
[6] International Atomic Energy Agency, "Safeguards Techniques and Equipment: 2011 Edition," 2011 Edition, Vienna (2011), p. 122.
[7] R. Scott Kemp, "On the Feasibility of Safeguarding Uranium Mines," *The Nonproliferation Review* vol. 13, no. 2 (2006), pp. 417-425.
[8] Akos Petoe, "Safeguards Obligations related to Uranium/Thorium Mining and Processing," International Atomic Energy Agency, Vienna, URAM 2009.
[9] "Comparison of Conventional Mill, Heap Leach, and In Situ Recovery Facilities," *Nuclear Regulatory Commission*, accessed July 20, 2017, https://www.nrc.gov/materials/uranium-recovery/extraction-methods/comparison.html.
[10] "Conventional Mining and Milling of Uranium Ore," *Uranium Producers of America*, accessed July 18, 2017, http://theupa.org/uranium_technology/conventional_mining/.
[11] Ibid.
[12] https://www.skydio.com/technology/

[13] "Comparison of Conventional Mill, Heap Leach, and In Situ Recovery Facilities," *Nuclear Regulatory Commission*, accessed July 20, 2017, https://www.nrc.gov/materials/uranium-recovery/extraction-methods/comparison.html.

[14] Canadian Nuclear Association, "Uranium Mining," https://cna.ca/technology/energy/uranium-mining/.

[15] Canadian Nuclear Association, "Uranium Mining," https://cna.ca/technology/energy/uranium-mining/.

[16] "In Situ Leach Mining of Uranium," *World Nuclear Association*, June 2017, http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/in-situ-leach-mining-of-uranium.aspx.

[17] Jacques Thiry and Sergio Bustos, "Heap Leaching Technology: Moving the frontier for treatment. Applications in Niger and Namibia," IAEA, Vienna, June 2014.

[18] Heavy Lift UAS from FoxTechFPV, accessed June 21, 2019 https://www.foxtechfpv.com/gaia-160-mp-heavy-lift-drone-arf-combo.html

[19] Hybrid Power UAS, accessed June 21, 2019, https://www.foxtechfpv.com/gaia-160-hybrid-hexacopter-arf-combo.html, https://www.harrisaerial.com/carrier-h6-hybrid-drone/

[20] "First Ever Hour-long Flight for Hydrogen Multi-Rotor Uav", accessed Jun 20, 2019, https://www.intelligent-energy.com/news-and-events/company-news/2019/01/08/first-ever-hour-long-flight-for-hydrogen-multi-rotor-uav-with-5kg-payload/

[21] "Metavista Breaks Guinness World Record of Multi-rotor UAV Flight" https://www.intelligent-energy.com/news-and-events/company-news/2019/04/16/metavista-breaks-guinness-world-record-of-multi-rotor-uav-flight-time-using-intelligent-energy-fuel-cell-power-module/

[22] "What is LIDAR?" *National Ocean Service*, accessed August 2, 2017, https://oceanservice.noaa.gov/facts/lidar.html.

[23] "Brashtech UAS with integrated Flash LIDAR", access June 20, 2019, https://brashtech.com/overview

[24] "A Workflow to Estimate Topographic and Volumetric Changes and Errors in Channel Sedimentation after Disturbance", accessed June 21, 2019, https://www.mdpi.com/2072-4292/11/5/586/pdf

[25] uGPS-RapidMapper, accessed June 21 2019, https://ugpsrapidmapper.com

[26] "Drone-based Volume Measurement Delivers Big Time-Savings to Mining," *DroneDeploy*, March 3, 2016, accessed July 31, 2017, https://blog.dronedeploy.com/drone-based-volume-measurement-delivers-big-time-savings-to-mining-eb684e748819.

[27] "Think 3D First to Commercialize 3D Drone Scanning," FARO, accessed June 18, 2019, https://www.faro.com/en-gb/case-studies/think-3d-first-to-commercialize-3d-drone-scanning/.

[28] "Uranium in Niger," *World Nuclear Association*, May 2017, accessed July 18, 2017, http://www.world-nuclear.org/information-library/country-profiles/countries-g-n/niger.aspx#.UUnKyFeMKcU.

[29] "eBee," *senseFly*, accessed July 12, 2017, https://www.sensefly.com/drones/ebee.html.

[30] "Pix4Dmapper Pro," *senseFly*, accessed June 18, 2019, https://www.sensefly.com/software/pix4d/.

[31] P.G. Martin et al., "3D unmanned aerial vehicle radiation mapping for assessing contaminant distribution and mobility," *International Journal of Applied Earth Observation and Geoinformation* vol. 52 (2016), pp. 12-19.

[32] "Uranium in Niger," *World Nuclear Association*, May 2017, accessed July 18, 2017, http://www.world-nuclear.org/information-library/country-profiles/countries-g-n/niger.aspx#.UUnKyFeMKcU.

[33] Michael East, "Safeguards Reporting and Verification for Uranium Mines," IAEA Training Meeting on Effective Regulatory and Environmental Management of Uranium Production, Darwin, August 13□17, 2012.

[34] J.W. MacFarlane et al., "Lightweight aerial vehicles for monitoring, assessment and mapping of radiation anomalies," *Journal of Environmental Radioactivity* vol. 136 (2014), pp. 127-130.

[35] Roy Pöllänen et al., "Performance of an air sampler and a gamma-ray detector in a small unmanned aerial vehicle," *Journal of Radioanalytical and Nuclear Chemistry* vol. 282, no. 2 (2009), pp. 433-437.

[36] Rishikesh Bharti, R. Kalimuthu, and D. Ramakrishnan, "Spectral pathways for exploration of secondary uranium: An investigation in the desertic tracts of Rajasthan and Gujarat, India," *Advances in Space Research* vol. 56 (2015), p. 1614.

[37] Rishikesh Bharti, R. Kalimuthu, and D. Ramakrishnan, "Spectral pathways for exploration of secondary uranium: An investigation in the desertic tracts of Rajasthan and Gujarat, India," Advances in Space Research vol. 56 (2015), pp. 1613-1626.

[38] Alexander Solodov, Adam Williams, Sara Al Hanaei, and Braden Goddard, "Analyzing the threat of unmanned aerial vehicles (UAV) to nuclear facilities," SAND2017-4308J, 2017.

[39] Geoffrey Shaw, "Uranium Mining: Safeguards and Physical Protection, Australian Experiences," IAEA General Conference: Uranium AEA Production: Prospects and Challenges, Vienna, September 15, 2009.

[40] Francesco Nex and Fabio Remondino, "UAV for 3D mapping applications: a review," *Applied Geomatics* vol. 6 (2014), pp. 1-15.

[41] "Unmanned Aircraft Systems (UAS)," *Federal Aviation Administration*, accessed June 18, 2019, https://www.faa.gov/uas/.