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ANALYSIS OF SELECT UNMANNED AERIAL SYSTEMS APPLICATIONS FOR INTERNATIONAL SAFEGUARDS

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Abstract

The extensive spread of unmanned aerial systems (UAS) technology combined with its decreasing costs and continuous integration with new sensor types may be used to support international nuclear safeguards. An expert elicitation exercise to prioritize potential UAS use cases for safeguards was conducted first. These cases were prioritized based on three criteria: safeguards impact, ability to address a current safeguards challenge, and acceptability to facility operators and the IAEA. Following prioritization, a detailed analysis of the select top rated applications was performed focusing on technology readiness of UASs to support selected safeguards applications, the effects on safeguards effectiveness and efficiency, and potential impact on normal facility operations. Analyses have shown that one of the applications evaluated is feasible for near-term deployment for IAEA use with UASs: survey of mining and concentration activities. This activity can be implemented using currently-available COTS UAS and associated sensor technology. Safety and security concerns are the lowest for this application, as uranium mines traditionally have minimal fragile or sensitive equipment on site.

1. INTRODUCTION

In the last several years, development of unmanned aerial system(s) (UAS) technology has experienced rapid growth due to advances in navigation and control technology, taking advantage of the economies of scale, and new sensor development in the mobile computing market. This has resulted in significant cost reductions that have seen small, agile UASs emerge as a multi-billion-dollar commercial market. Novel UAS applications for industries and government agencies are emerging almost on a daily basis. Based on expert assessment, UASs could be used as a platform for the deployment of a variety of monitoring technologies for International Atomic Energy Agency (IAEA) safeguards activities. Therefore, the current work focuses on analyzing the potential of applying UAS technology for safeguards use. The analysis includes:

- A survey of the current state of UAS technology, including a literature review of technical reports and commercial availability of UAS technology; an assessment of the relevant capabilities of UASs as well as the accompanying detection and monitoring systems mounted on board. This process may be challenging with the fast-paced evolution in this field as well as growing industry regulations;
- Analyzing the potential implications of the introduction of UAS technology on safeguards operational effectiveness and efficiency. The analysis assesses how UASs would alter the ability of IAEA inspectors to accomplish their tasks in an expedient and accurate manner;
- Analyzing the impact on operations of nuclear facilities. While the effectiveness of a safeguards inspection may be enhanced through the use of UAS technology, the negative impact on facility operations may render the implementation of this technology unnecessarily cumbersome or not acceptable.

2. SELECTED UAS APPLICATIONS AND SELECTION CRITERIA

Sandia National Laboratories (SNL) completed a prioritization exercise through a survey of safeguards experts in 2017, which prioritized potential UAS applications based on three criteria: safeguards impact, ability

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to address a current safeguards challenge, and acceptability to facility operators and the IAEA. The survey resulted in a prioritization table with a score assigned to all potential UAS applications. The intention of the prioritization table was to inform the selection of a final set for in-depth study. At the same time, it was not meant to be the only deciding factor, as the survey results may be affected by participant biases, limited number of responses, and other factors.

These applications were analyzed from the standpoint of technical means needed to accomplish them, final data analysis, and outcomes. With the objective to achieve the optimal technical and safeguards application variety, four tasks were selected for an in-depth analysis (in no particular order):

- Site Evaluation – Collection of detailed site information
- Survey of Mining and Concentration Activities – Collection of detailed site imagery-based information
- Nuclear Material Accountancy – Verification of container inventory
- Containment and Surveillance – Tag/Seal verification

3. EVALUATION OF TECHNOLOGY READINESS

UAS technology has experienced rapid growth in industrial and commercial use over the past several years. A large part of this evolution has been the result of technological developments reducing the cost and/or payload of UAS components and attachments. Miniaturization of remote sensing and surveillance equipment has allowed for the ability to affix cameras, radar, thermal imagers, hyperspectral imagers, and a vast array of additional equipment to a small lightweight unmanned aerial vehicle (UAV). The distinction between UAV and UAS comes with the components: the UAS includes the flying device (the UAV), payload, control elements, and communication systems [1]. GPS and satellite communication allow UASs to be piloted over large distances, acquire data with high precision, and transmit that data back to the operator in real-time. Newer UASs have the capability for the user to plan the path of the platform before its flight [2]. Automated features such as obstacle avoidance and return-to-home allow for additional safety [3]. However, in-door navigation is still challenging. Although progress is being made on the military side, it may be some time before improved technology reaches commercial use. TABLE 1 displays various typical UAS capabilities.

TABLE 1. TYPICAL UAS CAPABILITY RANGES

Capability	Typical Range
Imaging Cameras-Visual range (MP)	(12-20) [4],[5]
Payload (kg)	(1-9) [6],[7]
Cost (USD)	Varies widely, several hundred to several tens of thousands ~USD25k [8]
Flight Range (km)	(2-480) [9],[10]
Flight Time/Battery Life (mins)	(10-900) [11],[12]
Features such as: Obstacle avoidance, return-to-home, autonomous flight path, autonomous landing, first-person view (FPV)	Yes/No

Technical capabilities that could support selected UAS applications for international nuclear safeguards include:

- 2-D Imaging – Photos or Video
- 3-D Imaging
- Volumetric Measurements
- Hyperspectral Imaging
- Thermal Imaging
- Radiation Detection
  - Topographic characterization of the radiation dose or count rates on site
  - Real-time on-board gamma spectroscopic measurements

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- Collection of air samples

– RFID Readers
– Optical Character Recognition (OCR) and Barcode Readers

Detailed assessment of the current state of each of these technologies is given in the following sections.

4. EFFECTS ON SAFEGUARDS EFFECTIVENESS AND EFFICIENCY

The evaluation included is given from the following two perspectives: effectiveness and efficiency. Subject matter experts commonly refer to the "effectiveness and efficiency" of safeguards when discussing applied technologies, but there are no universally accepted definitions for these terms, nor is there a unified methodology for assessing them. Herein the current discussion, these terms are redefined to assist in conveying how applied UAS technologies could potentially affect the international safeguards system. For the purposes of the current work these terms are defined for the most informative analysis of UAS applications for safeguards. Furthermore, various measures are specified to aid in assessing each specific application.

Herein, "effectiveness" is defined as *the ability of an inspector (or the UAS technology) to attain quality data in order to draw a safeguards-relevant conclusion*. As the quantity/quality of data increases, the accuracy of a drawn conclusion may increase. Furthermore, a distinction is made between the acquisition of known types of data and the acquisition of new types of data: data taken from sources otherwise impossible to attain without UAS. In addition, UAS usability, portability, and assistance to inspectors' situational awareness is investigated for a more complete assessment of safeguards effectiveness.

Herein, "efficiency" is defined as *the ratio between the quantity of data (used to draw said conclusion) and the time and costs in which it takes to acquire*. Hence, as claimed in the current chapter, if applied UAS technology can 1) increase the number of data points in a given amount of time or 2) can decrease the amount of time and/or costs for acquiring the same number of data points, the overall efficiency increases. The potential costs for introducing UAS technology into safeguards activities could ostensibly consist of four components: 1) initial equipment costs; 2) equipment maintenance and sustainability; 3) costs of transporting a UAS to/from the inspected site; and 4) training costs for inspectors to operate the UAS and perform data analysis.

4.1. Costs and Sustainability

The evaluation of costs and sustainability assessment provided here applies almost equally to all safeguards applications described in the study. Therefore, to avoid repetition, it is provided once before analyses of effectiveness and efficiency of individual applications.

As with many types of equipment, the initial costs of UAS equipment will likely be a small fraction of the total cost of ownership (TCO). The remaining three cost components mentioned above - equipment maintenance and sustainability, transportation, and training - would create the majority of the overall TCO for UASs.

The costs of equipment testing and acceptance by the IAEA should also be included into analysis as a significant initial investment into implementation of this new technology. As new technologies are being developed, additional expenses on testing and replacing existing tools will be needed. Since the advancement in the area of UASs is extremely fast, this could be a significant factor for consideration.

Based on a review of available technology, initial costs for equipment suitable for safeguards applications subject of the current study will be on the order of several tens of thousands USD. The costs will vary depending on the type of UAS vehicle employed and on the measurement tools attached. Some of these costs may be mitigated by implementing a shared-use arrangement with a site. In this instance a site would maintain and operate its own UAS and IAEA inspectors will only attach equipment needed for the inspection.

In the case of an IAEA-owned UAS, transportation costs should be on the same order of magnitude as the equipment that is currently being transported by inspectors, such as portable radiation detectors. Modern UASs have small form factors and can be fitted in a small-to-medium size suitcase. Payload tools are also small and light, which would make it easier to transport them.

Significant training costs will be incurred, but they are difficult to estimate since the magnitude will depend on many factors, such as the type of equipment the training is conducted for, training location, training

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duration, training frequency, etc. Sample training course curricula for UAS operators in industrial applications are available online, with one lasting a total of 50 hours [13]. Initially, only a few inspectors would need special UAS operation training. As this type of training becomes more widespread, some of the costs could be offset by reducing training on older technology retired from safeguards applications.

The maintenance and sustainability costs of any UAS will consist of several components. The first of these is cost of repairs and component replacement. Most of the UAS components, especially measurement equipment, are expensive, and therefore this would be a significant portion of the maintenance costs. Frequency of repairs would depend on the environmental operating conditions, including the presence of dust/sand and extreme temperatures. In sustainability of a UAS, consideration should be given to how often the systems may need to be updated/replaced. Accelerating progress in technology development may create a problem of acquisition of 'older' replacement parts, which would lead to necessity of replacing the whole system to a newer version.

An additional potential cost associated with operating UASs would be aviation insurance. Some States may legally require insurance to cover liability and UAS equipment itself.

4.2. Site Evaluation

4.2.1. Effectiveness

Employing UAS technology for site verification would significantly increase the quality and the amount of data an inspector is able to collect. Current approaches rely on printed maps and site descriptions, as well as inspectors' prior knowledge of a site. UASs would have the capability to create a digital map with detailed imagery of buildings and other objects on site. Imagery obtained in subsequent site verification activities can be compared to original (baseline) data. Pre-flight inspections/survey of an area would improve situational awareness. This application of UAS technology has the highest potential impact on safeguards effectiveness in the context of the study for site evaluation, providing unprecedented levels of detail and significantly automating inspection activities at the site.

4.2.2. Efficiency

Use of UAS technology for site evaluation activities would significantly automate certain inspectors' activities, such as visual observations, and reduce the time needed for completing the required tasks. UASs would allow for a fly-through of the site, while collecting imagery and other (if allowed) data. Analysis of collected data could be done 'on the fly' and sent back to the inspector, which would reduce the amount of time needed even further. The most significant reduction in inspection time would be achieved by using pre-programmed flight paths, eliminating the need for manual operation. However, it should be noted that significant resistance from the site operator on allowing fully automated fly-throughs is expected.

On the other hand, the required time for setting up the system and going through preparation for the flight could be significant. Depending on the rules established by the site operator, certain site activities may have to be stopped and arrangements made for the safe and secure operation of a UAS over a site (see Chapter 5 for more details). Potential gains in inspection time may be diminished by preparation for the task.

Overall, in the current framework defined, there is no clear indication of changes in safeguards efficiency. New and higher quality data would be captured, but additional resources and potentially greater inspection times will be needed.

4.3. Survey of Mining and Concentration Activities

4.3.3. Effectiveness

Since satellite imagery has a limited capability to conduct 3-D analysis and volume assessment for the IAEA, it is expected that light detection and ranging (LiDAR) attached to a UAS will enhance data quality significantly due to being conducted at much closer distances. Satellite imagery resolution is typically limited to

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61 cm while those from LiDAR are in the several-cm level ranges [14],[15]. UASs may be able to provide higher resolution hyperspectral imaging relative to satellite, although there are barriers to effective integration of this technology with UASs [16].

Overall, relative to current inspection practices the use of UASs would provide a way to collect detailed information (visual imagery, volumetric assessment, change detection). Therefore, implementation of UAS technology for safeguards inspections of uranium mines would bring a significant increase in inspection effectiveness.

4.3.4. Efficiency

For most nations currently, IAEA inspectors do not perform a complete inspection of the full area of a mine. Therefore, the use of UASs would allow for a new activity in the field for inspectors. This would require additional resources and time compared to current activities, but would allow for a detailed assessment of mine capacity, current state, significant changes from last inspection, etc.

In the framework of the current project, the efficiency would increase, as significant volumes of additional data will be collected relative to current practices. Additional resources will be required for implementation, however.

4.4. Verification of Container Inventory

4.4.5. Effectiveness

Employing UASs for verification of container inventory would provide a significant level of automation and speed to the process of verification of container presence and location. With implementation of RFID technology or barcode readers, a more comprehensive inventory can take place instead of random sampling. Radiation measurements using UAS-attached detectors will not provide the same quality of data as inspector measurements, mainly due to the limitations on detector size and amount of shielding that can be put on a UAV. Shielding is critical in this type of application due to high background from surrounding containers.

Based on this, according to the definition of effectiveness outlined previously, the only area where UASs would provide an increase in safeguards effectiveness is automated verification of container inventory, but not in performing radiation measurements. However, even for container verification, there is still significant stagnation in technology development. For effective UAS implementation, universal use of RFID tags or barcode tags placed in locations accessible for UASs would be needed.

4.4.6. Efficiency

Taking into account the costs and regulatory challenges required to implement UASs for safeguards inspection at nuclear facilities, it appears that no gain in efficiency will be achieved for container inventory verification. UASs are not currently capable of performing all tasks done by inspectors, and significant resources will be needed in order to implement tasks that UASs are capable of.

4.5. Tag/Seal Verification

4.5.7. Effectiveness

Only moderate gains in effectiveness are possible for implementation of UASs for tag and seal verification. There is a limited space where UASs can be used, mostly for verification of tags and active seals.

4.5.8. Efficiency

With consideration of the significant financial resources and regulatory challenges required to implement UASs in safeguards inspection activities, it appears that no gain in efficiency will be achieved for tag and seal verification.

5. EFFECTS ON FACILITY OPERATIONS

The IAEA's GOV/2784 report has mandated that the imposition of safeguards verification measures not burden states with "excessive costs" or "cumbersome measures to facilitate verification" [17]. In addition, it mentions that safeguards developments must consider a state's "need to preserve industrial and commercial secrets and other confidential information" when implementing safeguards measures. The current chapter explores potential effects of implementing UAS technology in safeguards inspections on nuclear facilities' operations, safety and security.

5.1. Facility Safety

UASs have entered the consumer market with little rigorous safety-assessment analysis performed. Most UASs for consumer use are lightweight and would cause little damage when colliding with most outdoor industrial features of a nuclear facility. However, the interior of a nuclear facility may contain significant hazardous material or fragile equipment. Furthermore, the required sensing equipment affixed to a UAS for safeguards inspections may increase the weight sufficiently to cause significant damage upon collision with a non-hardened object or human. The interaction/collision of a UAS with material, equipment, or personnel could result in unacceptable consequences for the operator and the State.

5.2. Facility Security

One of the biggest concerns of nuclear facility operators in terms of introducing UAS on site is facility security. There is significant literature available regarding the security impact of UASs on nuclear facilities [18], and further detailed analysis is beyond the scope of the study. Multiple States and facilities are now including UASs in their Design Basis Threat (DBT) and are implementing defense mechanisms against them. Therefore, significant work will need to be done to alleviate some of these security concerns and develop capabilities and mechanisms to distinguish between a rogue UAS and legitimate UAS performing a safeguards inspection.

5.3. Regulatory Concerns

Many States have their own rules and federal regulations for UAS use [19]. 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. This may require inspectors to have licenses in multiple countries, making the process complicated and difficult to maintain.

6. CONCLUSIONS

Analyses have shown that one of the applications evaluated is feasible for near-term deployment for IAEA use with UASs: survey of mining and concentration activities. This activity can be implemented using currently-available COTS UAS and associated sensor technology. Safety and security concerns are the lowest for this application, as uranium mines traditionally have minimal fragile or sensitive equipment on site. Visual surveillance with a high-resolution camera and video imaging as well as 3-D imaging, change detection, and volumetric measurements with LiDAR could be used to obtain safeguards-relevant information more quickly and possibly at lower costs than currently performed by IAEA inspectors during site evaluations or survey of a mining/concentration site.

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Site verification using UASs is feasible from a technological standpoint even with current COTS. However, since most of the nuclear installations are designated as ‘no-fly zones’, significant concerns and pushback from nuclear operators are expected. Technology for container inventory and tag/seal verification is improving, but not yet ready for near-term IAEA deployment. Any effort to implement RFID, barcode, or OCR technology would require additional industry-wide effort to place tags in an accessible location on containers and make them resistant to high temperatures, shocks, and environmental conditions. Radiation signature measurements of UF_6 cylinders using detectors mounted to a UAS would be difficult due to high radiation background and limitations on the amount of shielding a UAS can carry on board.

Safeguards effectiveness and efficiency were specifically defined for the purposes of the study, as there are no formal definitions of these terms. All conclusions on effects on safeguards effectiveness and efficiency are made within the defined framework. The cost analysis has shown that the initial costs of UASs with measurement equipment for all analyzed applications would be on the order of several thousands to several tens of thousands USD. However, initial costs are only a small fraction of the TCO, as a majority of the costs will be incurred for training of UAS operators, maintenance, system upgrades, etc.

For uranium mine inspections and site evaluations, safeguards effectiveness will increase significantly, as the quality and quantity of data collected will go up. For inventory and tag/seal verification, only moderate or no increase in effectiveness is expected, as UASs would not be capable of performing all of the tasks currently done by inspectors. Furthermore, significant upfront investment will be needed for standardizing tags/RFIDS/seals placement.

Assessment of safeguards efficiency for each specific application was mostly qualitative. Each application would require significant initial investment. Based on the analysis, efficiency will increase for mining inspection and site verification activities, mainly because of significant improvements in the quality and quantity of data collected. For container and tag/seal verification, efficiency is not expected to increase. This is because of the need for a human operator to perform certain tasks, significant initial investments, and regulatory obstacles.

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