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LABORATORY DEMONSTRATION OF A MULTISENSOR UNATTENDED CYLINDER VERIFICATION STATION FOR URANIUM ENRICHMENT PLANT SAFEGUARDS

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Abstract

The objective of safeguards is the timely detection of the diversion of a significant quantity of nuclear materials, and safeguarding uranium enrichment plants is especially important in preventing the spread of nuclear weapons. The IAEA's proposed Unattended Cylinder Verification Station (UCVS) for UF_6 cylinder verification would combine the operator's accountancy scale with a nondestructive assay system such as the Passive Neutron Enrichment Meter (PNEM) and cylinder identification and surveillance systems. In this project, we built a laboratory-scale UCVS and demonstrated its capabilities using mock UF_6 cylinders. We developed a signal processing algorithm to automate the data collection and processing from four continuous, unattended sensors. The laboratory demonstration of the system showed that the software could successfully identify cylinders, snip sensor data at the appropriate points in time, determine the relevant characteristics of the cylinder contents, check for consistency among sensors, and output the cylinder data to a file. This paper describes the equipment, algorithm and software development, laboratory demonstration, and recommendations for a full-scale UCVS.

Keywords: enrichment plant safeguards, unattended monitoring, neutron measurements, data fusion

Introduction

Unattended monitoring systems have always played an important role in the field of nuclear safeguards [1]. These systems provide continuous monitoring of nuclear facilities without the need for an International Atomic Energy Agency (IAEA) inspector to be present. They offer the highest level of safeguards assurance and minimize the impact to both the operator and the IAEA by reducing the frequency and duration of inspections. As commercial technology improves to allow the IAEA to better collect, organize, store, and analyze large sets of disparate data streams, the use of these unattended monitoring systems will likely continue to grow.

Collecting vastly more data than is currently done in places where unattended monitoring is not currently used may permit the IAEA to loosen uncertainty requirements for individual instruments. With less error from sampling, can the IAEA accept more measurement error? For decades, the safeguards community has been pushing the uncertainty targets of nondestructive assay (NDA) systems closer to those of destructive analysis (DA). But, is it possible that through expanded use of continuous, unattended monitoring and multisensor data fusion that *more* data could trump *better* data? Random sampling is a fundamental concept in how safeguards are done today, but it is an inferior alternative to analyzing the full dataset [2].

Safeguarding sensitive fuel cycle facilities such as those used for uranium enrichment is a critical component in the international nuclear nonproliferation regime. The IAEA has proposed an unattended monitoring system, dubbed the Unattended Cylinder Verification Station (UCVS), for 100% verification of product, feed, and tails cylinders within an enrichment facility while reducing the need for routine measurements and sampling during on-site inspections [3]. The UCVS would combine the operator's accountancy scale with a NDA system such as the Passive Neutron Enrichment Meter (PNEM) [4,5] and technologies for cylinder identification and surveillance.

The objective of this project was to build and demonstrate a laboratory-scale UCVS by combining the PNEM, an electronic scale, a barcode reader, and a camera. The system provides an example of how multisensor data fusion and automated data processing could be used to increase the efficiency, effectiveness, and reliability of safeguards verification at uranium enrichment plants. The work was performed over the course of the 9-week 2013 Los Alamos Dynamics Summer School (LADSS). This paper includes a description of the hardware components that make up the UCVS demonstration system, the algorithms developed for integrating the various data streams, the surrogate materials that were used to mimic UF_6 cylinders, the results of the demonstration, and concludes with some thoughts on how the demonstration system could help inform the development of a full-scale UCVS for enrichment plant safeguards.

Equipment

The equipment used for this project consisted of the following:

- PNEM neutron detector pods,
- Shift register,
- Electronic scale,
- Barcode reader,
- Camera,
- Data collection and analysis computer, and
- Mock UF_6 cylinders.

The experimental setup is shown in Figure 1. The PNEM uses the Singles neutron count rate to determine ^{235}U mass and the Doubles count rate to determine ^{235}U enrichment in UF_6 cylinders. The neutron data from the PNEM is collected with the Canberra JSR-15 Handheld Multiplicity Register (HHMR) [6] and processed using the Multi-Instrument Collect (MIC) software, which was developed by Los Alamos National Laboratory as a universal platform for data acquisition in unattended mode operation [7]. The JSR-15 is a shift register that counts and records the total number of pulses received as well as correlated neutron counts. The scale we used measures object weights up to 60 kg with a sensitivity of 0.02 kg and indicates whether or not the measured weight is stable; this information is sent to the computer through a RS-232 serial port.

The barcode reader is motion activated. It takes in a barcode passed under it as a string of digits and sends it as input to the computer via a RS-232 serial port.

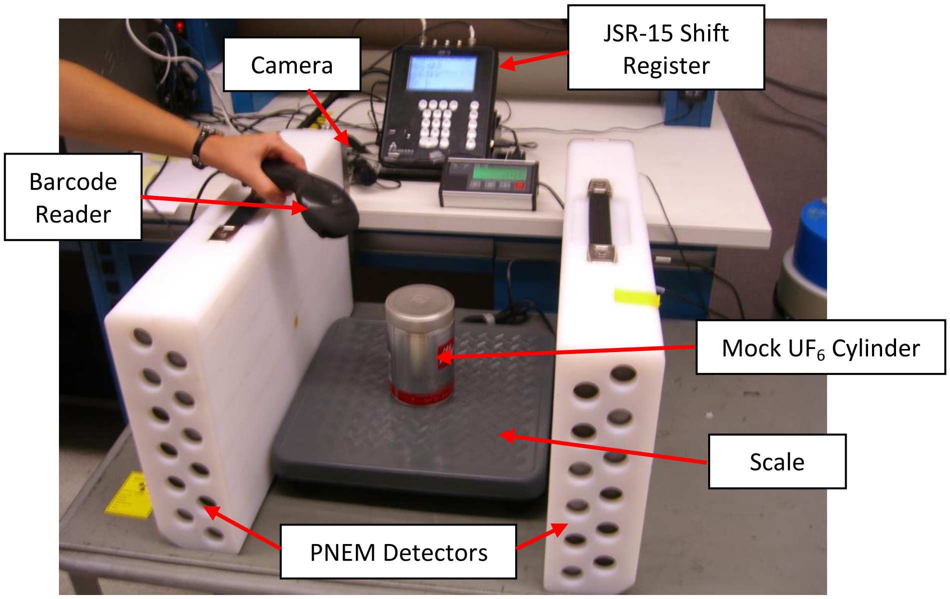

Figure 1. Experimental setup for the UCVS laboratory demonstration.

The surveillance camera we used in this system is an Axis 2420 IP camera. The video is uploaded to the computer and processed by an open source camera management software called iSpy [8]. In addition to the Axis camera, we investigated using a Microsoft Kinect. The Kinect would have given a greater range of image processing and tracking abilities, but the Axis was chosen over the Kinect due to difficulties having the Kinect programs, written in a Microsoft SDK, communicate with the rest of the system written in Python.

The mock UF_6 cylinders were comprised of weighted canisters that contained ^{252}Cf sources with a range of neutron emission rates. ^{252}Cf is often used as a surrogate for uranium because it emits correlated spontaneous fission neutrons.

Algorithm & Software Development

Recognizing that the whole is often greater than the sum of its parts, multisensor data fusion involves the combination of complementary sensors in a way that provides more accurate and reliable information than individual sensors can provide alone. The goal of this project was to build and demonstrate an unattended monitoring system that would combine data streams from the various components of the UCVS in order to verify the contents of cylinders containing nuclear material.

The first step in developing the algorithms was to define the use case. The UCVS is envisioned to be built around the operator's accountancy scale at an enrichment plant. Throughout daily operations, UF_6 cylinders containing varying amounts of total UF_6 and enrichment levels would be placed on the scale, remain there for the allotted count time, and then be removed. In our laboratory-scale version of the UCVS, the PNEM detector pods and scale collect continuous data. The "facility operator" places a cylinder on the scale, scans the cylinder's barcode, allows the cylinder to remain on the scale for the allotted count time, and then removes the cylinder. The camera's data stream is motion triggered. The next cylinder is then placed on the scale and the process is repeated. In the laboratory demonstration of UCVS, all data is collected into day files that are post-processed after all data is collected (i.e., the sensor integration does not run in real time as data is being collected).

In order to address this use case, we wrote various Python scripts and integrated them together in a graphical user interface such that the scale, barcode reader, and MIC software all stream in data simultaneously. After the data streams have finished, all of the data is integrated and post-processed to calculate uranium mass and enrichment, check for any inconsistencies in the uranium enrichment value calculated using two different combinations of neutron measurement and scale data, and flag any procedural irregularities such as an object being placed on the scale without having a barcode scanned, having a barcode scanned with no recorded object weight, or having a recorded weight with no count measurement. Figure 2 shows a flowchart of how the software integrates all of the data streams and produces useful output files.

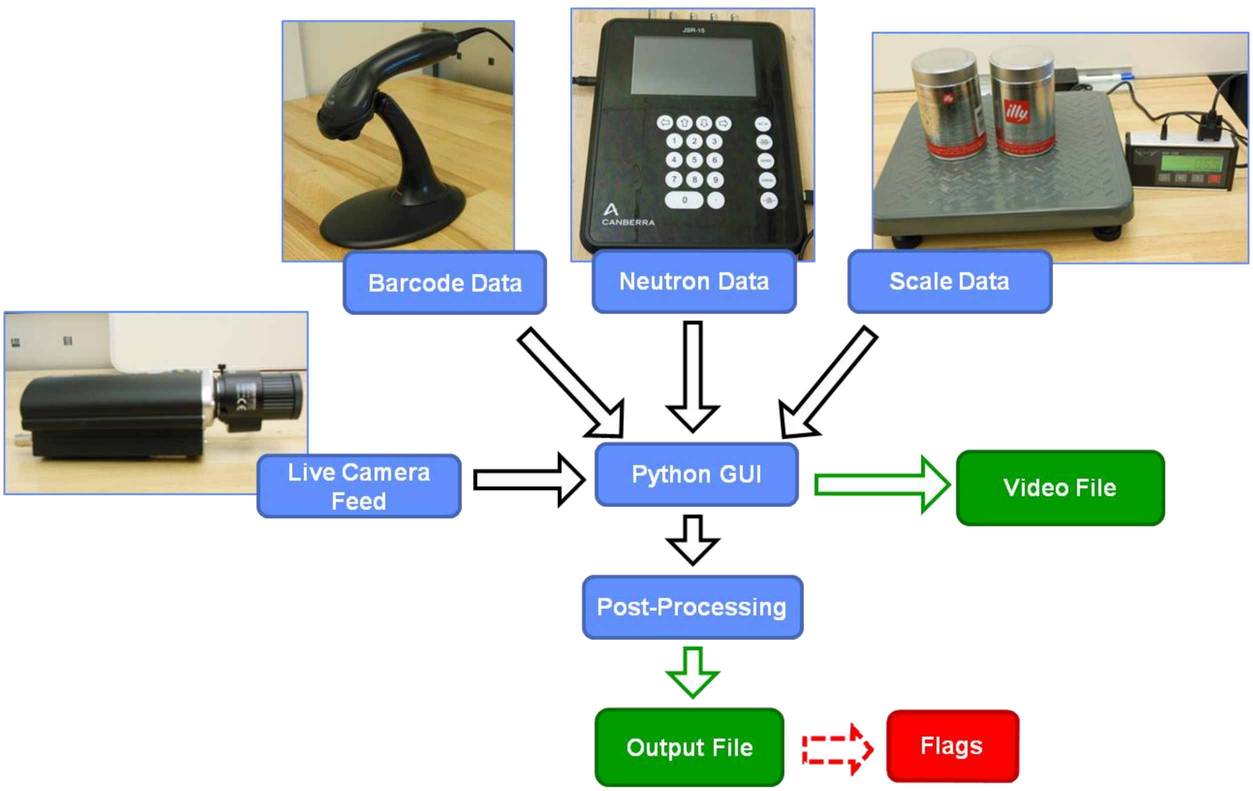

Figure 2. Software flowchart.

The basic functionality of the software is the following:

- Collect data from all of the sensors,
- Recognize when a cylinder is placed on/taken off the scale,

- Obtain a cylinder ID,
- Obtain surveillance camera footage of the cylinder,
- Obtain a gross cylinder weight and convert to total uranium mass,
- Snip the Singles and Doubles continuous neutron data at the appropriate points in time to calculate Singles and Doubles count rates for each cylinder,
- Apply a calibration curve to convert the Singles count rate into ^{235}U mass and the Doubles count rate into ^{235}U enrichment,
- Combine the ^{235}U mass determined with the Singles count rate and the total uranium mass determined with the scale data to calculate a redundant value for the ^{235}U enrichment ($E_{235} = m_{235} / m_U$),
- Check for consistency between the enrichment value calculated with the Doubles count rate vs. the enrichment value calculated by combining the Singles count rate and scale data within a defined uncertainty tolerance,
- Output the cylinder information to a text file, and
- Flag any inconsistencies in the enrichment calculations or procedural irregularities.

Once the use case and basic functionality of the mock UCVS were defined, all of the sensors were assembled together and several sets of test data were collected on which to build the signal processing algorithms. This allowed exploration of things like data formats, file locations, and time sequencing for each of the sensors.

The test data were also used to construct calibration curves for the neutron and scale data. Five weighted canisters that contained ^{252}Cf sources of various strengths were used as a surrogate for UF_6 cylinders. In order to mimic the data streams that would be collected on real UF_6 cylinders, fake calibration curves were constructed for ^{235}U mass and enrichment using the Singles and Doubles count rates from the ^{252}Cf measurements. Mock ^{235}U mass and enrichment values were assigned to each calibration cylinder such that the "enrichment" calculated with the Doubles count rate equaled the "enrichment" calculated by combining the "^{235}U mass" derived from the Singles count rate and the "total uranium mass" derived from the scale. The mock data for each calibration cylinder is given in Table 1, and the neutron calibration curves that were constructed are shown in Figure 3.

Table 1. Simulated uranium data for mock UF_6 cylinders containing ^{252}Cf sources.

Barcode ID	**^{235}U Enrich. [wt%]**	**^{235}U Mass [kg]**	**UF_6 Mass [kg]**	**Singles [cps]**	**Doubles [cps]**
111111111	0.71	0.010	2.08	1198.53	104.97
3333333333	1.8	0.026	2.14	2225.78	489.56
44444444	3.0	0.040	1.97	3342.07	976.47
777777	4.0	0.053	1.96	4202.60	1459.32
9999999	4.9	0.068	2.05	5318.92	2224.08

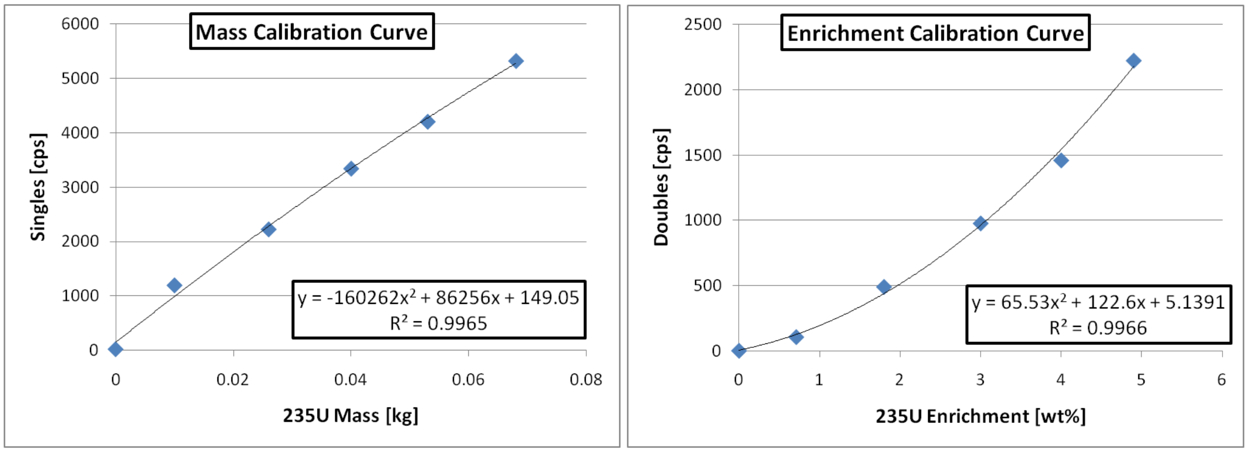

Figure 3. ^{235}U mass and enrichment calibration curves for the PNEM measurements of canisters containing ^{252}Cf sources of various strengths.

In order to integrate the data from each of the sensors to obtain meaningful information from them, we developed a signal processing algorithm and coded into a series of Python scripts. The algorithm first reads in all of the most recent data files and converts the MIC data from binary into an ASCII text format. The algorithm then searches the scale data file to recognize when objects were placed on and removed from the scale. This is done by reading each line of the scale output file and comparing the scale data between the neighboring lines. If both values are indicated by the scale as stable weights and the difference between the two weights is greater than the uncertainty associated with the scale, then the algorithm notes that something was either placed on or taken off of the scale as well as the time that the event occurred. The scale weight represents the gross weight of the cylinder. In order to calculate the total uranium mass, the algorithm subtracts the tare weight of the cylinder from the gross weight and converts net UF_6 mass into uranium mass.

The algorithm then reads in the barcode data file, taking in all of the barcodes scanned and associated time stamps. These times are compared to the times at which items were placed on the scale. If the barcode time stamp coincides with the time an object was placed on the scale to within a small time window, then the barcode, corresponding object mass, and time of scale placement are all written to a list. If there is a barcode scanned that does not correspond to any scale placement time, that extraneous barcode and its corresponding time are printed to the output file with an error message indicating a procedural irregularity. Similarly, if there is a scale placement time that does not correspond to any barcode time, then that weight and its associated scale placement time are also written to the output file with an error message indicating a procedural irregularity.

The algorithm then takes that list of barcodes, weights, and times and reads in the parsed MIC data that corresponds to the times at which items with barcodes were on the scale. The relevant neutron counts (R and R+A bins) are averaged over that time window and converted into Singles and Doubles count rates for each item. Using the polynomial coefficients from their respective calibration curves, the Singles and Doubles count rates are used to calculate the ^{235}U mass and enrichment, respectively, of each object that has passed through the system. For each object, a second enrichment value is calculated by dividing ^{235}U mass calculated with the Singles count rate by the total uranium mass obtained from the scale. These two enrichment values are then compared to see if they match within a predefined uncertainty tolerance. If the two values are consistent, all of the data for that object (barcode, gross cylinder weight, UF_6 mass, uranium mass, ^{235}U mass and enrichment values, errors, start time, and stop time) are written to the output file. If the two enrichment values are not consistent, then all of the above data are still written to the output file with an "enrichment inconsistency" flag that indicates the barcode number and scale placement time of the cylinder.

In addition to the PNEM detector pods, scale, and barcode reader, the Axis 2420 surveillance camera also provides a live video feed into the computer that can be viewed in real time. With the iSpy software, the camera is also equipped with real-time motion detection as well as recording capabilities. Each time movement above a certain threshold is detected within a certain amount of time (i.e. when a cylinder is placed in the measurement cavity), the software highlights the motion and records the video stream for a specified amount of time, including a buffer period before the motion detection. The program then saves the video to a folder on the computer. Using a Python script that is executed by iSpy, the time stamp for each motion event is recorded in a text file that can be viewed along with the output from the post-processor for the PNEM, scale, and barcode data streams.

Demonstration & Results

Once the post-processing software was completed, we conducted a laboratory demonstration to test its capabilities. In addition to testing whether the system could correctly identify and verify the contents of the five calibration cylinders, we tested several scenarios that were designed to cause consistency or error flags. A successful test was considered to be one in which the enrichments and other values of interest were calculated and recorded properly by the post-processor and any inconsistencies in the enrichment values or procedural irregularities, such as weight placed on the scale with no barcode scanned, were flagged in the output file.

A description of the test cases used in the demonstration is given in Table 2. Test cases 1, 3, 4, 7, and 9 were measurements of the calibration cylinders with no spoofing or irregularities. In test case 2, a barcode was scanned but no cylinder was placed in the measurement cavity. In test case 5, a cylinder was placed on the scale without scanning a barcode. In test cases 6 and 8, cylinders with too much and too little weight, respectively, for the corresponding ^{252}Cf source strength were placed on the scale in order to test the ability of the post processor to flag inconsistencies, or potential spoofing cases, between the two enrichment calculations.

The continuous data streams from the demonstration are shown in Figure 4, and a screenshot from the surveillance camera is shown in Figure 5. The data were run through the post-processor, and the results are given in Table 3. For each test case, the table provides the net UF_6 and total uranium mass from the scale output, the ^{235}U mass calculated from the Singles count rate, the enrichment value calculated by combining the scale and Singles output ($E_{235,S}$), the enrichment value calculated from the Doubles count rate ($E_{235,D}$), the absolute (ΔE_{abs}) and relative (ΔE_{rel})

differences between the two enrichment values, and the dwell time for the cylinder in the UCVS. The error flags are also included at the bottom of the table.

Table 2. Description of test cases for the UCVS laboratory demonstration.

Test Case	Cylinder Description
1	Calibration cylinder with barcode 111111111
2	Barcode 22222222 scanned but no cylinder placed in the measurement cavity
3	Calibration cylinder with barcode 3333333333
4	Calibration cylinder with barcode 44444444
5	Calibration cylinder with barcode 44444444 placed in the measurement cavity but barcode was not scanned
6	Spoofing case: cylinder with barcode 6666666; cylinder contained a weaker ^{252}Cf source than expected for the mass of the cylinder
7	Calibration cylinder with barcode 777777
8	Spoofing case: cylinder with barcode 8888888; cylinder contained a stronger ^{252}Cf source than expected for the mass of the cylinder
9	Calibration cylinder with barcode 9999999

The laboratory demonstration showed that the signal processing algorithm and code worked as expected. All nine test cylinders were acknowledged by the code. In all but test case 2, where a barcode was scanned but no cylinder was placed on the scale, the code correctly recorded the gross cylinder weights and calculated the UF_6 and total uranium masses. The code also snipped the continuous neutron signals at the appropriate times, calculated Singles and Doubles count rates, and converted those values to ^{235}U mass and enrichment.

For the demonstration, we set the uncertainty tolerance on the consistency check between the two enrichment calculations to 10% relative. The code flagged three of the test cases with enrichment inconsistencies. These cases are highlighted in red in Table 3. The cylinder we used for test case 1 was a calibration cylinder, so we did not expect the cylinder to be flagged with an inconsistency prior to seeing the measurements. However, the low count rate for that cylinder combined with a relatively short count time resulted in a large statistical uncertainty. Because of this, the enrichment values calculated with the two different combinations of sensors resulted in a relative difference of more than 10%, and the inconsistency was flagged by the code. In this case, the measurement, which was based on surrogate nuclear materials and a fabricated calibration curve, did not turn out as expected, but the code did function exactly as expected.

Test cases 6 and 8 were also flagged as inconsistencies. This was expected as the test cases were designed to mimic scenarios that involved either equipment malfunctions or intentional spoofing by an adversarial operator. These cases really highlight the utility of multisensor data integration. Combining the signals from multiple sensor types and checking for consistency between redundant values has two big advantages over looking at each component independently: (1) it can help alert the IAEA quickly to equipment failures or calibration issues and (2) it is much harder to spoof multiple sensors simultaneously than single, independent sensors.

The code treated the remaining six test cases as expected. Test cases 2 and 5 resulted in procedural error flags due to the barcode being scanned with no cylinder and vice versa. Test cases 3, 4, 7, and 9 were based on calibration cylinders and produced no flags or error messages. The laboratory demonstration of the UCVS showed that the code was able to meet the functionality requirements of the system successfully. Future improvements to the system could include making the software more robust and user friendly, incorporating background subtraction functionality, and providing a real-time indicator of when each cylinder should be removed from the scale based on the neutron counting statistics.

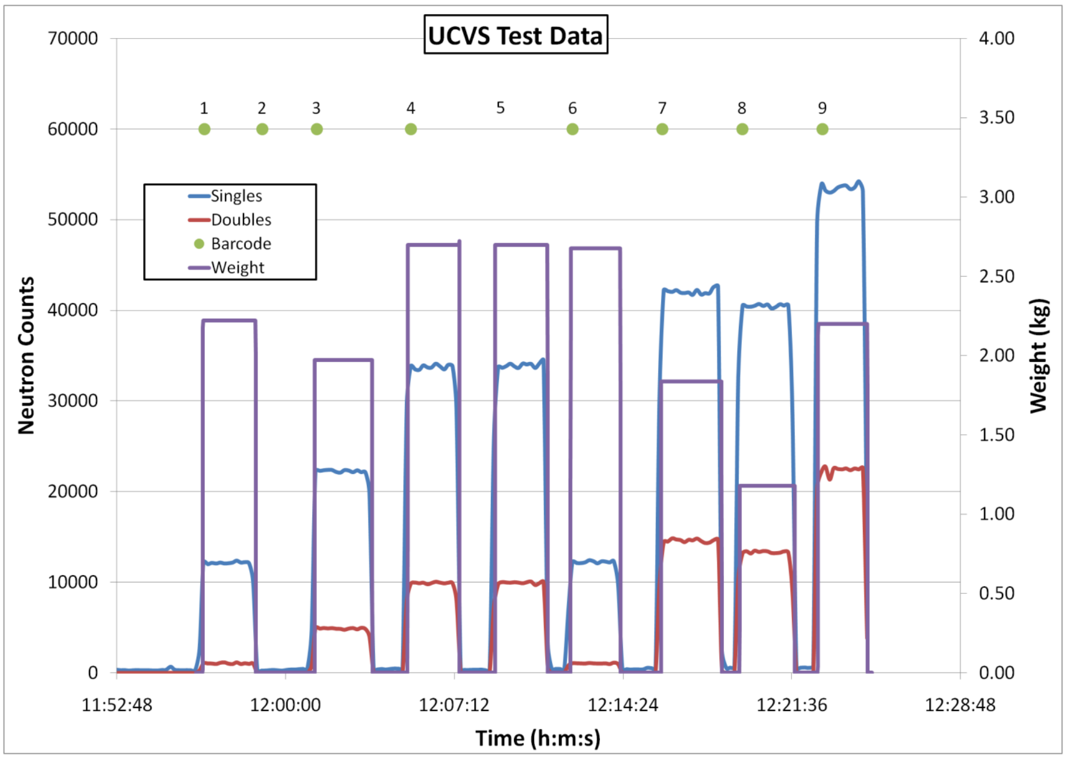

Figure 4. Continuous data streams from the UCVS laboratory demonstration.

Figure 5. Screenshot from the surveillance camera footage with motion detection.

Table 3. Post-processor output from the laboratory demonstration.

Barcode ID	Net UF_6 (kg)	m_U (kg)	m_{235} (kg)	$E_{235,S}$ (wt%)	$E_{235,D}$ (wt%)	ΔE_{abs} (wt%)	ΔE_{rel} (%)	Start		End	
111111111	**1.97**	**1.33**	**0.012**	**0.94**	**0.59**	**0.34**	**57.98**	**13:42:10**	**7/24/2013**	**13:48:22**	**7/24/2013**
3333333333	2.01	1.36	0.025	1.85	1.94	0.09	4.9	13:52:08	7/24/2013	13:52:24	7/24/2013
44444444	1.91	1.29	0.041	3.21	3.07	0.14	4.49	13:58:55	7/24/2013	14:04:09	7/24/2013
###########	1.91	1.29	0.041	3.15	3.05	0.1	3.36	14:04:35	7/24/2013	14:09:43	7/24/2013
6666666	**1.89**	**1.28**	**0.012**	**0.97**	**0.59**	**0.38**	**65.00**	**14:10:24**	**7/24/2013**	**14:15:31**	**7/24/2013**
777777	1.85	1.25	0.051	4.08	3.72	0.36	9.66	14:16:49	7/24/2013	14:21:58	7/24/2013
8888888	**1.11**	**0.75**	**0.05**	**6.67**	**3.65**	**3.01**	**82.43**	**14:22:38**	**7/24/2013**	**14:27:50**	**7/24/2013**
9999999	1.95	1.32	0.072	5.45	5.15	0.3	5.85	14:29:08	7/24/2013	14:34:20	7/24/2013
Weight registered but not barcode start Wed Jul 24 14:04:35 2013 end Wed Jul 24 14:09:43 2013											
Barcode 22222222 scanned but no weight start Wed Jul 24 13:52:08 2013 end Wed Jul 24 13:57:23 2013											
Enrichment inconsistency between 2013-07-24 13:42:10 and 2013-07-24 13:48:22 ID 111111111											
Enrichment inconsistency between 2013-07-24 14:10:24 and 2013-07-24 14:15:31 ID: 6666666											
Enrichment inconsistency between 2013-07-24 14:22:38 and 2013-07-24 14:27:50 ID: 8888888											

Conclusions

In this project, we built a laboratory-scale UCVS for enrichment plant safeguards in order to demonstrate and test the feasibility of our approach to multisensor data integration. The UCVS software we developed collects and fuses data streams from the PNEM, a scale, barcode reader, and a network camera. Integrating continuous data from multiple sensors brought along many unforeseen challenges. The majority of the challenges came about in interfacing the various hardware components, such as the barcode scanner, with the software platform we chose to use. There were also challenges associated with file management, exposing data in a consistent format, and time stamping.

If the IAEA moves forward in developing the UCVS for enrichment plant safeguards, the conceptual design of the UCVS presented here could be modified to meet specific user requirements. Additional sensors, signatures, or software platforms could be incorporated as needed. For example, the NDA Fingerprint role of a UCVS could include sensors to characterize the spatial distribution of UF_6 within the cylinder. Laser Doppler vibrometry (LDV) has recently been shown to be a possible technique for this purpose [9]. As another example, one recognized shortfall of using the Singles neutron count rate to quantify ^{235}U mass in UF_6 cylinders is assumption of a $^{234}U/^{235}U$ ratio. The Singles cadmium subtraction can also be used to determine ^{235}U mass, but it has a different dependence on ^{234}U content than the Singles count rate alone. It has been shown that the cadmium subtraction can be used as a qualitative check on the ^{234}U content of UF_6 that could be used as a flag to indicate if a particular cylinder has a $^{234}U/^{235}U$ ratio outside the calibrated range (e.g., reprocessed UF_6, cylinders that contain light-element impurities, etc.) [10]. This feature could be incorporated into an unattended system by adding a dedicated cadmium-covered neutron detector pod to the PNEM. We also chose to use MIC software for the unattended neutron data collection, but the PNEM detector pods are also compatible with RADAR/CRISP [11].

There are still many real-world design questions that need to be addressed before a full-scale UCVS could be used for enrichment plant safeguards. Beyond performance questions associated with the individual component technologies that would constitute the UCVS, there are design issues associated, more generally, with unattended monitoring systems. For example, what types of state-of-health checks on the equipment would help alert the IAEA when an instrument was at or near a failure state? How robust is the system to failure of one or more of its components? How will data authentication, security, and transmission be handled? How could tamper-indicating features be incorporated into the mechanical or electrical components? Furthermore, we have demonstrated in this paper one way to integrate multiple data streams at the instrument level for the UCVS, but can those concepts be extended to the facility level by integrating the UCVS with other unattended systems at a uranium enrichment plant?

In conclusion, the first 20 years of safeguards was focused on verifying the correctness of a State's declaration, or detection of a diversion from declared facilities. In the 1990s, undeclared activities in Iraq, South Africa, and North Korea exposed weaknesses in this system and paved the way for the Additional Protocol. Strengthened safeguards represented a transformational shift from a system designed to verify only the correctness of a State's declaration to one that attempts to verify the correctness and completeness of a State's declaration. We are now at another 20-year mark, and the field of safeguards seems primed for a second transformational shift. The convergence of ideas such as information-driven safeguards and the State Level Concept with the exponential growth of consumer sensor technology and big data concepts may provide the backbone for a new era in safeguards. Unattended, multisensor data fusion solutions to safeguards verification problems we have demonstrated with the UCVS have the potential to allow the IAEA to do more with its increasingly strained resources. Mayer-Schonberger and Cukier summarized it well in their book *Big Data: A Revolution That Will Transform How We Live, Work, and Think*: "In some ways, we haven't yet fully appreciated our new freedom to collect and use larger pools of data. Most of our experience and the design of our institutions have presumed that the availability of information is limited. We reckoned we could only collect a little information, and so that's usually what we did. It became self-fulfilling. We even developed elaborate techniques to use as little data as possible. One aim of statistics, after all, is to confirm the richest findings using the smallest amount of data. In effect, we codified our practice of stunting the quantity of information we used in our norms, processes, and incentive structures."

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