REMOTE & VIRTUAL INSPECTIONS
AN UPDATE ON PRINCETON’S WORK ON NUCLEAR VERIFICATION

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ABOUT US

Science, technology, and policy for a safer and more peaceful world
CONSORTIUM FOR MONITORING, TECHNOLOGY, AND VERIFICATION (MTV)

Five-year project, funded by U.S. DOE, 14 U.S. universities and 13 national labs, led by U-MICH
Princeton participates in the research thrust on Signals & Source Terms for Nuclear Nonproliferation
Verification Research at Princeton

(A very brief overview)
GRAND (VERIFICATION) CHALLENGES

www.verification.nu
GRAND (VERIFICATION) CHALLENGES

- Establishing confidence in the absence of undeclared stocks or production
- Confi nding the authenticity of nuclear warheads (upon dismantlement)
- Verifying numerical limits on declared nuclear warheads
- Monitoring ongoing activities at military nuclear sites
- Monitoring nuclear warheads in storage
- Confirming completeness of baseline declarations using nuclear archaeology methods
HOW NOT TO GIVE AWAY A SECRET

CONTINUE IMPROVING TECHNOLOGIES AND APPROACHES
Work on information barriers with a particular focus on certification and authentication; in particular, identify joint hardware and software development platforms.

REINVENT THE PROBLEM: NEVER ACQUIRE SENSITIVE INFORMATION TO BEGIN WITH
Explore fundamentally different verification technologies and approaches; for example, avoid need for trusted hardware or seek alternatives to onsite inspections at certain sensitive facilities.

REVEAL THE SECRET
Requirement to protect sensitive information is typically the main reason for complexity of verification approaches; for example, mass of fissile material in a nuclear weapon.

Source: Author (top and bottom) and Johannes Tobisch (middle)
EXAMPLE #1

Zero-knowledge Verification
SUPERHEATED DROPLET DETECTORS MAY OFFER A WAY TO IMPLEMENT SECURE INSPECTIONS BY AVOIDING DETECTOR-SIDE ELECTRONICS

Superheated C-318 fluorocarbon (C₄F₈) droplets suspended in aqueous gel
Tailor-made by d’Errico Research Group, Yale University
Sensitive to neutrons with $E_n > E_{min}$
Designed to be insensitive to $\gamma$-radiation

Active volume ........... : 6.0 cm³
Droplet density ........... : 3500 cm⁻³
Droplet diameter ...... : ~100 µm
Absolute Efficiency ... : $4 \times 10^{-4}$
ZERO-KNOWLEDGE NEUTRON RADIOGRAPHY
WITH PRELOADED, NON-ELECTRONIC (BUBBLE) DETECTORS

Detector array (each pixel corresponds to one bubble detector)

Radiograph (never measured)

Valid item

Invalid item

Small deviations from $N_{\text{MAX}}$  
Significant deviations from $N_{\text{MAX}}$ (2.0, 2.5, 3.0 sigma)

ZERO-KNOWLEDGE NEUTRON RADIOGRAPHY
(EXCALIBUR @ PPPL)

E. Gilson, A. Glaser, R. J. Goldston, and J. Jeon, The EXCALIBUR Neutron Source, 63rd Annual INMM Meeting, July 2022
EXAMPLE #2

Inspection Systems based on Gamma Signatures
INFORMATION BARRIER EXPERIMENTAL (IBX)

Red Pitaya single-board computer (redpitaya.com)
Xilinx Zynq 7010, SoC with FPGA and ARM A9
14-bit ADC, 125 million samples per second

PROTOTYPE OF AN ABSENCE MEASUREMENT SYSTEM
USING PASSIVE GAMMA-RAY DETECTION

“SIMPLICITY THROUGH OBsolescence”

(STANDARD SODIUM-IODIDE DETECTOR & 12-BIN TEMPLATE)

M. Kütt and A. Glaser, PLOS ONE, October 2019, doi.org/10.1371/journal.pone.0224149
Toward Remote & Virtual Inspections
FROM ONSITE TO REMOTE INSPECTIONS

PROS & CONS OF ONSITE INSPECTIONS

Onsite inspections remain the “gold standard” for IAEA safeguards and nuclear arms-control verification.

Inspections tend to be costly and are often considered intrusive, especially in the arms-control context.

CAN WE (PHYSICALLY) “SEPARATE” HOST & INSPECTOR?

Many concerns could be addressed and resolved if inspectors were not “physically” present onsite.

As part of our MTV efforts, we explore various remote inspections techniques with a particular emphasis on robotic inspections.

Source: ukni.info (top) and microsoft.com (bottom)
3.4 MDV FOR ARMS CONTROL

3.4.1 Capability Needs

... Treaties that include weapons in storage or weapons designed for shorter-range delivery systems are anticipated to require new MDV techniques. As a minimum, such treaties would likely require access to storage areas either directly or remotely, and confirmation of warhead count (either a baseline confirmation or through routine/challenge inspections).

EXAMPLE #3

Robotic Inspections
ROBOTIC INSPECTIONS

THE IDEA IS NOT NEW

“The ROBIN provides a potential tool that ... allows the inspector to collect data inside a facility without actually entering that facility ... [and] limits the potential disclosure of sensitive technology.”

Frank F. Dean, ROBIN: A Way to Collect In-Plant Safeguards Data with Minimal Inspector Access, SAND82-1588C, Sandia National Laboratories, Albuquerque, New Mexico, 1982

IAEA ROBOTICS CHALLENGE

“Some of the most common tasks undertaken by IAEA nuclear safeguards inspectors involve making repetitive measurements in locations that can be difficult to access and/or have elevated radiation levels. This is an area where robotics has the potential to play a useful role.”


Source: SRI International (Shakey, 1966–1972, top) and IAEA (bottom)
POSSIBLE APPLICATIONS IN NUCLEAR SAFEGUARDS

Confirming the absence of undeclared activities in gas-centrifuge enrichment plants

- Detecting hidden feed & withdrawal stations in cascade areas
- Monitoring (declared) feed & withdrawal areas in the plant

POSSIBLE APPLICATIONS IN ARMS-CONTROL VERIFICATION

Confirming that a neutron field in a storage facility remains unchanged

- Robot should not “learn” or “remember” measurement data
- Use template-matching approach that results in simple non-sensitive output (e.g. 8-bit number) after inspection

Source: president.ir (top) and commons.wikimedia.org (D5481026, bottom)
N-SpecDir Bot

Boron-coated straw (BCS) detectors embedded in a polyethylene cylinder
One 3-detector (pictured) and two 6-detector systems available
Method for “single-shot” directional measurements
Experimentally-benchmarked MCNP model
EXPERIMENTAL CALIBRATION
SPECTRAL SENSITIVITY

Front-to-back ratio indicative of the (average) energy of incident neutrons

Response of a distributed energy source can be predicted by weighting the monoenergetic results by the detector efficiency

DIRECTIONAL SENSITIVITY

Cosine model
(for “single-shot” measurements)

\[ S_i = A + B \cos (\theta_i - \theta_0) \]
REDUCING SYSTEMATIC ERROR

Uncertainty is analytically propagated from the counting statistics to the directional estimate.

Doubling the detectors yields the expected $\sqrt{2}$ improvement.

Directional uncertainty of order unity is achievable for high count rates with low background.

Searching for a Source

(when there is not supposed to be one)
PARTICLE FILTER
FOR SOURCE LOCALIZATION

Robot follows a predefined raster pattern and updates particle weights with each measurement
ONGOING & FUTURE WORK

CHARACTERIZING THE NEW 6-DETECTOR SYSTEMS

Measurements at Princeton Plasma Physics Laboratory, October 2022
using a PuBe source at PPPL’s Calibration and Service Laboratory (CASL)
ONGOING & FUTURE WORK

EXPERIMENTAL DEMONSTRATION OF SIX-DETECTOR SYSTEMS
Implement the cosine model for “finding” a source with/without reflection and with/without the particle filter at PPPL; search for a source; measure application-relevant sources

PATH PLANNING, SEARCH STRATEGIES, AND SOURCE LOCALIZATION
Various types of obstacles: transparent, reflective, partially and fully absorbing
Different exploration strategies and localization methods (or absence confirmation)

USE CASE: N-SpecDir Bot for Safeguards & Arms-Control Applications
Find a withdrawal cylinder within a row of centrifuges and/or centrifuge hall
Need for more realistic test beds

Source: Authors (top), IBRoomba (middle), president.ir (bottom)
Can we confirm that the neutron field in a storage facility has remained unchanged between inspections...

...without revealing any sensitive information about the facility or its contents in the process?
EXAMPLE #4

Virtual Inspections
Can we remotely follow certain (allowed) activities that the host performs?
VIDEO BROADCAST

KEY REQUIREMENTS

SECURITY & PRIVACY
How to follow relevant activities without also capturing additional information that is considered sensitive but irrelevant for the task at hand?

DATA TRANSMISSION & INTEGRITY
How to transmit the footage to an offsite location, especially from the interior of a hardened and highly secured building? (Can it be done in real-time?)

LIVE VERIFY & LOCAL VERIFY (Johnston and Warner, 2010)
How to ensure that the footage is recorded in real-time? (How to preclude replay attacks?)
How to ensure that the data is transmitted from the correct location?

Source: IAEA (top and middle) and author (bottom)
EVENT-BASED VISION

FEATURES

- Extremely low bandwidth, no redundant data
- Very low power consumption (~ 100 mW)
- Asynchronous, fast data acquisition (µs-scale)
- High-dynamic range (> 120 dB)
- Sensitive to relative changes, not absolute values
- Commercially available since early 2010s
- Resolution: originally ~ 320 x 240 pixels

Currently moving to megapixel designs
“NOTHING TO SEE HERE”

EVENT-BASED VISION FOR INTRINSIC INFORMATION SECURITY

Event-based camera

Traditional (frame-based) camera

“Secret” information visible at inspected site

Recorded at TU Berlin, June 2022, courtesy of Guillermo Gallego
EXAMPLE #5

Virtual Reality
VIRTUAL REALITY
AS A TOOL FOR THE JOINT DEVELOPMENT OF NEW VERIFICATION APPROACHES

THE ORIGINAL IDEA
Create open and flexible virtual environments to explore new verification concepts and approaches

(... which could also lay a basis for live exercises and new policy initiatives)

CURRENT MAIN FOCUS OF PROJECT
Examine fundamental questions related to interactivity, user experience, and presence in virtual environments; but also explore “cheating scenarios” relevant for assessing the effectiveness of different verification approaches

Source: Authors
Demonstration of earlier project at the UN, Geneva on the margins of a meeting of the Group of Governmental Experts on nuclear disarmament verification, Palais des Nations, May 2018

Source: Pavel Podvig
SUMMARY AND OUTLOOK

(IN LIEU OF CONCLUSIONS)

PERSISTENT AND EMERGING VERIFICATION CHALLENGES

25 years of research and development have not (yet) produced the technologies needed to verify future arms-control agreements.

Remote and virtual inspection techniques could play an important role in future arms-control verification and safeguards.

RE-IMAGINING NUCLEAR DISARMAMENT VERIFICATION

Explore verification approaches that minimize the need of access to sites and treaty accountable items or avoid measurements on those.

Consider approaches that offer “on-ramps,” i.e., that start off simple and can accommodate “upgrades” later on.

Source: Sandia National Laboratories (top) and IAEA, flickr.com/photos/iaea_imagebank/albums/72157659464420989 (bottom)
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