TOWARD A ROBOTIC MULTI-TOOL FOR NEUTRON MEASUREMENTS IN SUPPORT OF REMOTE INSPECTIONS

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Introduction and Motivation

Leverage the mobile nature of a **robotic neutron detector** to characterize a neutron field and identify anomalies

N-SpecDir Bot and containerized Cf-252 source at PPPL TFTR Test Cell.
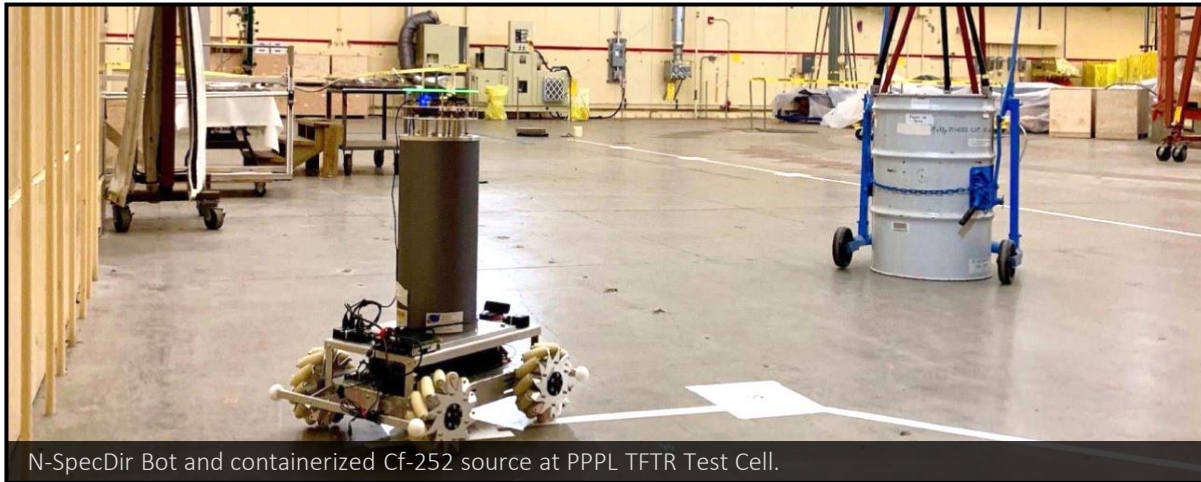
Boron-coated straw detectors embedded in poly; One 3-detector and two 6-detector systems available

Method for "single-shot" directional measurements
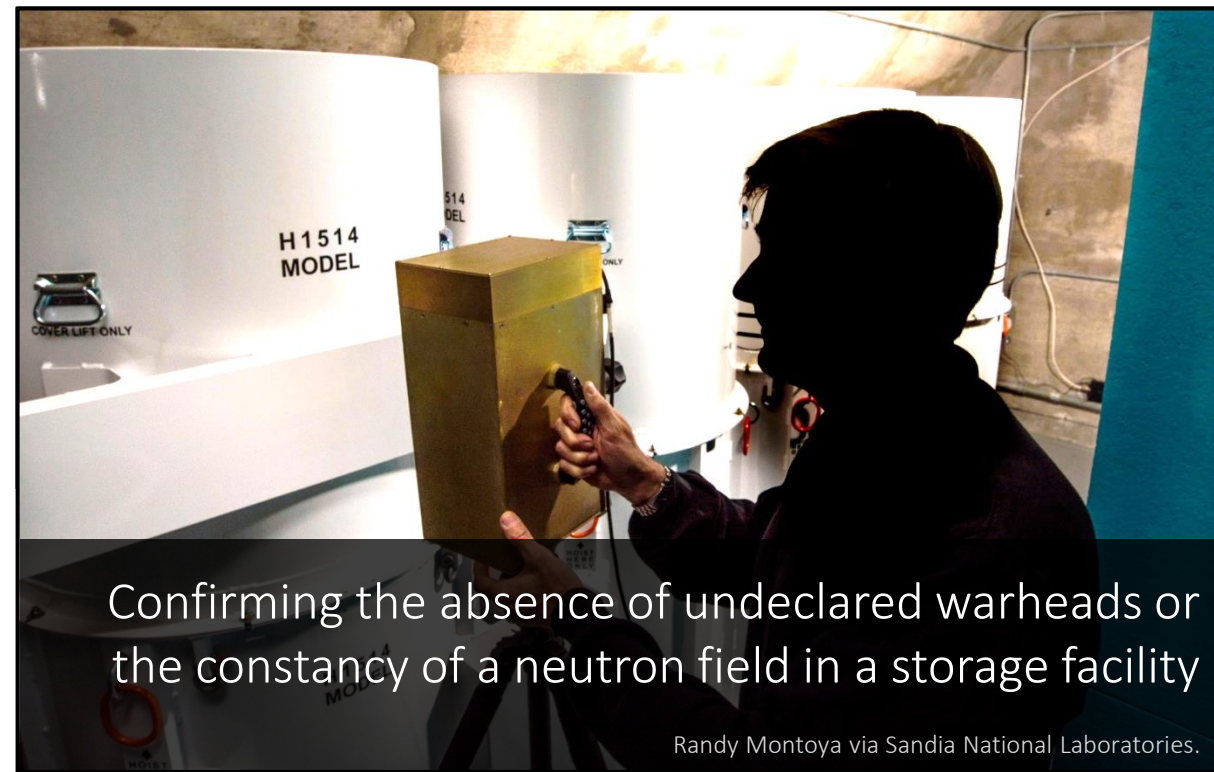
Experimentally-benchmarked MCNP model

Demonstrate a **unified approach** for localization of an anomalous source, absence confirmation, and spatial template matching

IAEA Imagebank, Dean Calma. Safeguards Inspection at URENCO, Almelo, Netherlands. 13 October 2015.

Robotic inspectors may be more effective and efficient and less intrusive than their human counterparts for verification tasks in scenarios when no significant [neutron] sources or changes are expected

Mission Relevance

Developing and implementing a new remote, and potentially autonomous, solution for **safeguards** (detecting and monitoring the nuclear fuel cycle) and **arms control** (monitoring weapons storage, reduction, and dismantlement)
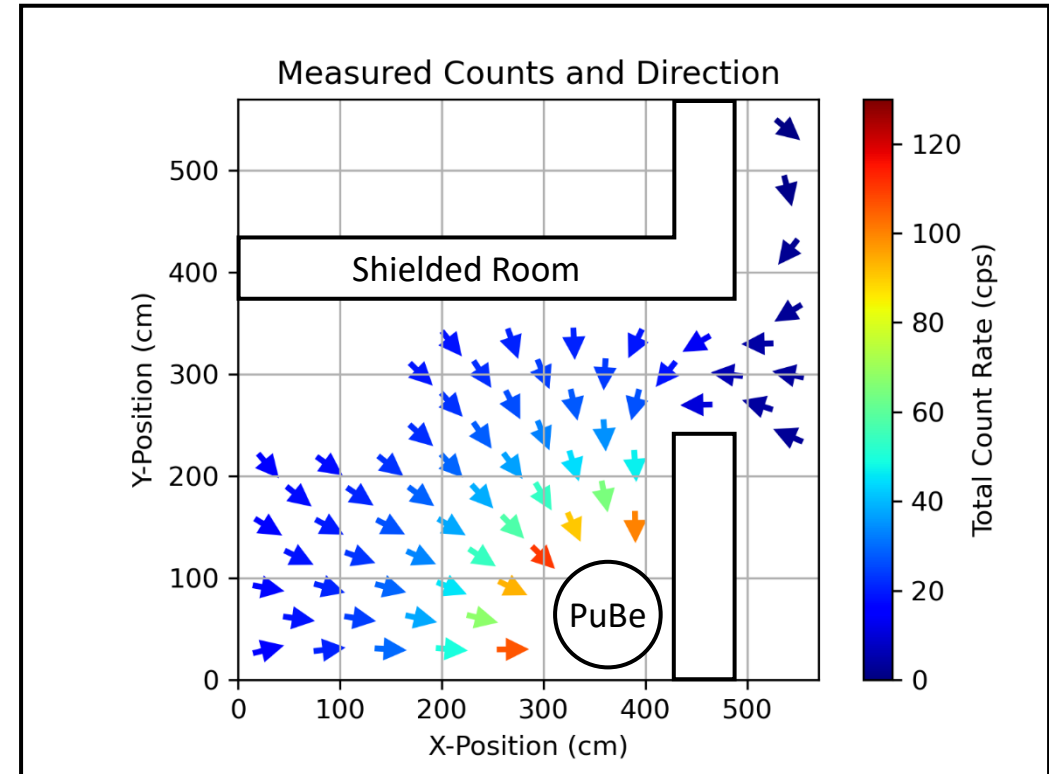

Detecting clandestine withdrawal stations in a cascade or undeclared LEU feed stations in gas centrifuge enrichment plants; feed cylinder or spent fuel monitoring; etc.

U.S. Department of Energy.

H1514 MODEL

Confirming the absence of undeclared warheads or the constancy of a neutron field in a storage facility

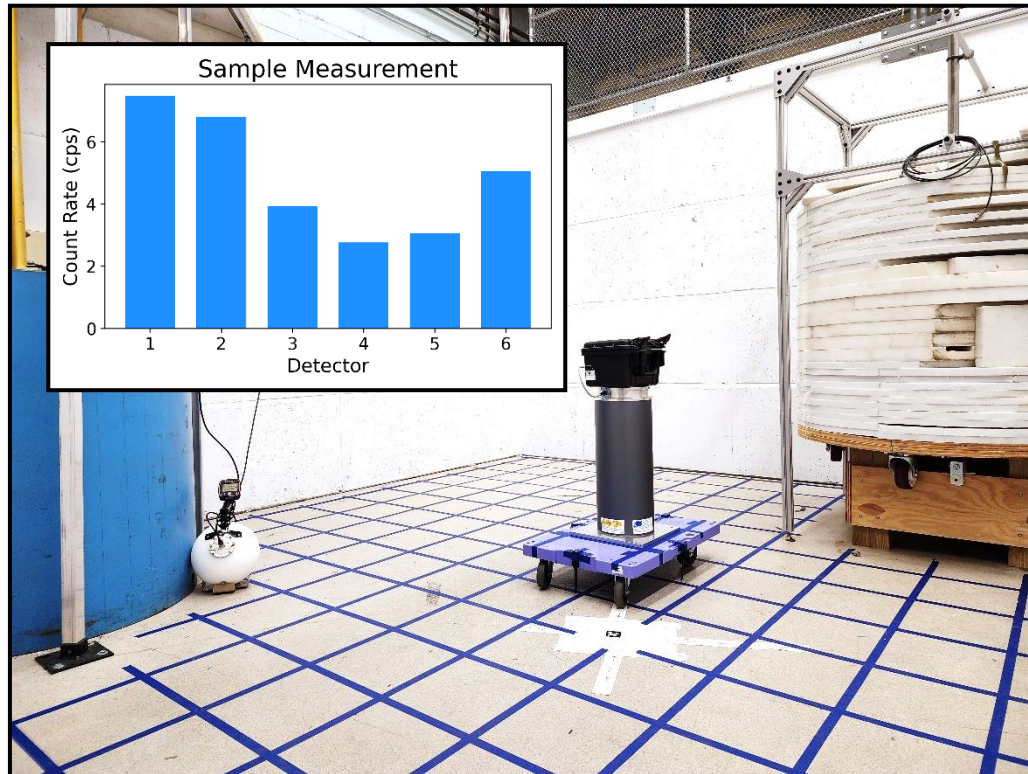Randy Montoya via Sandia National Laboratories.

Technical Approach

Starting from a simplified particle filter using **grid-based recursive Bayesian filtering**, we introduce several improvements which are applicable to nonproliferation and arms control applications, particularly concerning absence confirmation and spatial template matching

[1] Allow for the prediction of **unknown background radiation**

[2] Include the possibility of **"zero-intensity sources"** to verify the absence of sources

[3] Adapt the particle filter to **template matching** with prior measurements
Template matching permits zero-intensity and negative sources

[4] Incorporate **physical limitations** on the placement of potential sources
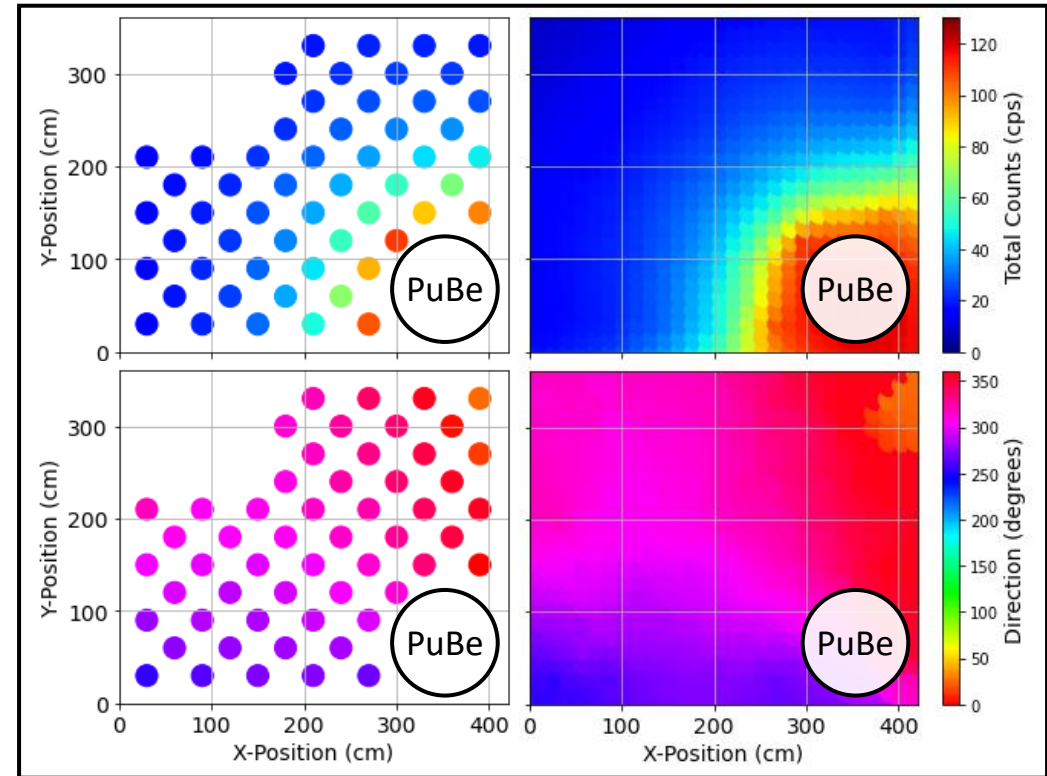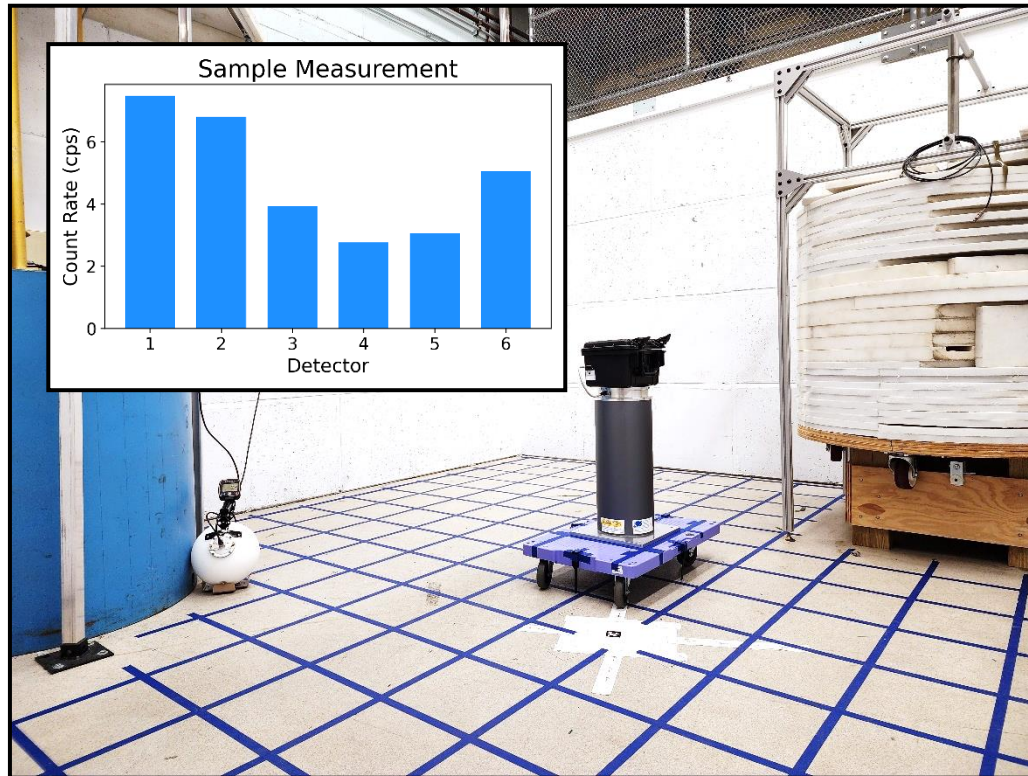
Template Measurement

Template measurement (5-minute, 30-cm checkerboard) of **containerized PuBe source at PPPL**'s Calibration and Service Laboratory (CASL)

Radial basis function interpolation on discrete measurements using **orientation-corrected** three nearest neighbors
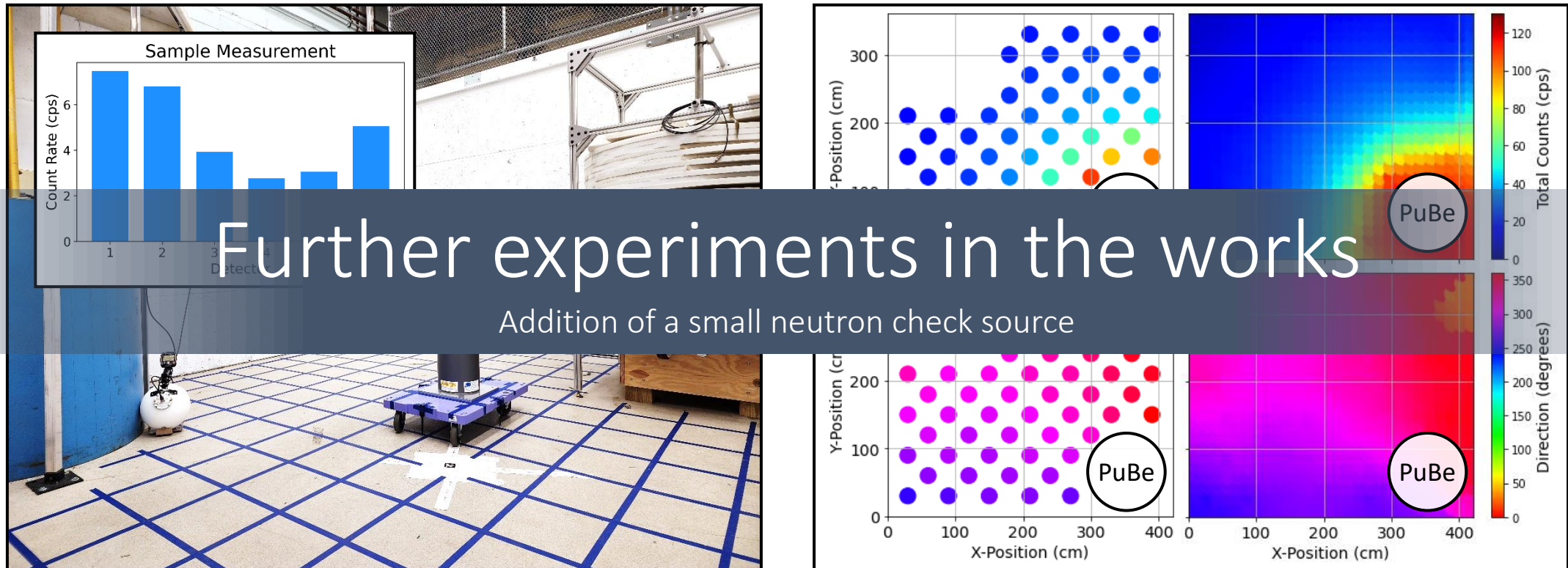
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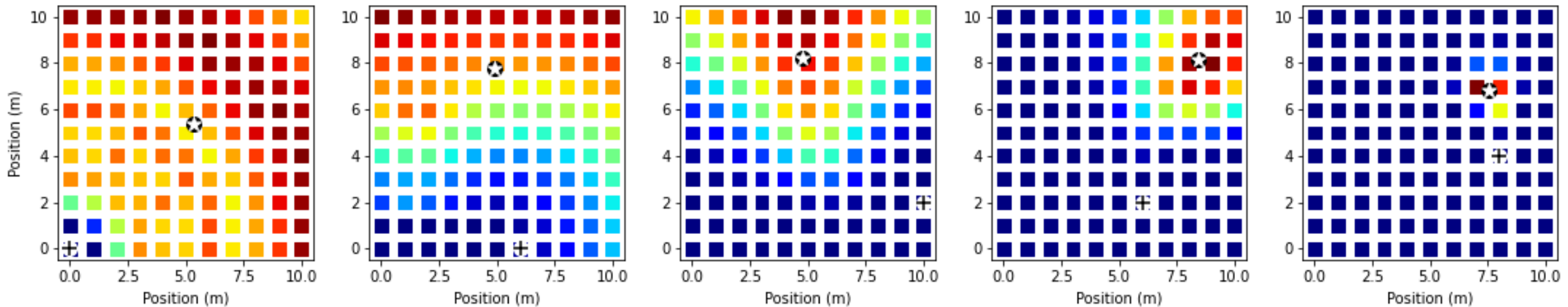
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Further experiments in the works
Addition of a small neutron check source

Radial basis function interpolation on discrete measurements using **orientation-corrected** three nearest neighbors

Template Matching Demo

Template matching with the **updated particle filter** demonstrating both source localization and absence confirmation with *no code or parameter modifications*
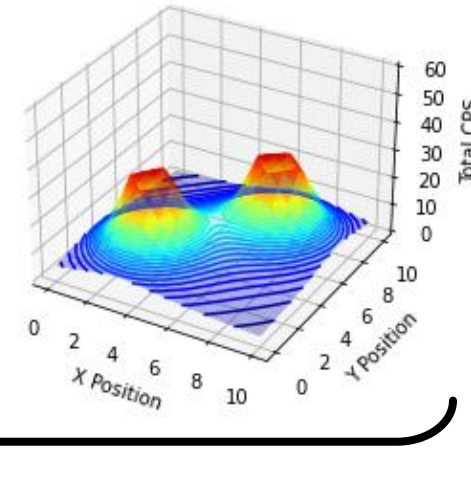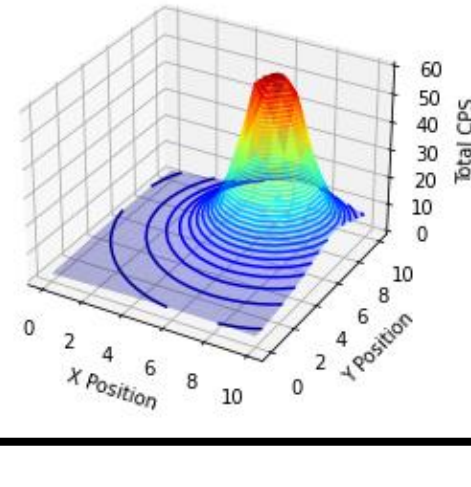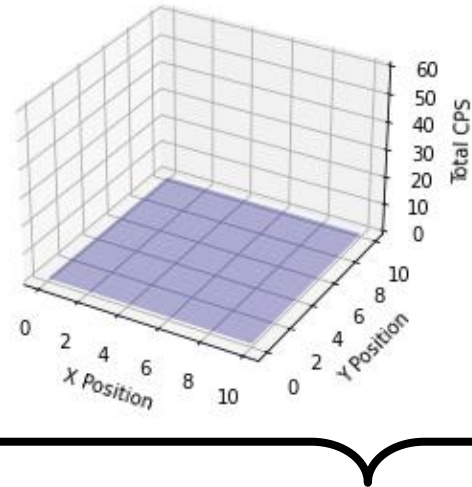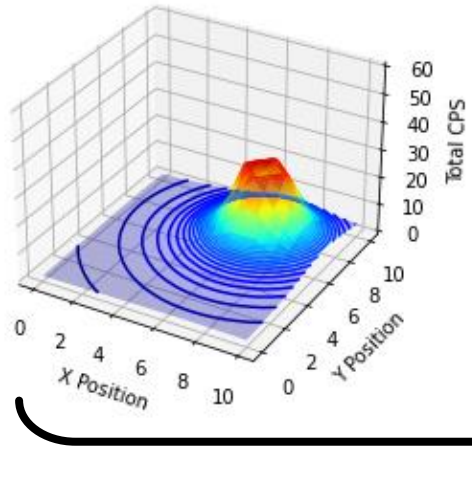

Particle filter recursively updates the belief over source hypotheses while the N-SpecDir Bot travels around the environment acquiring [simulated] measurements

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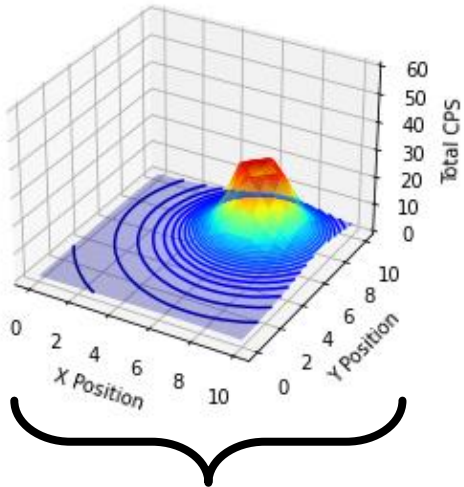
Template **Measurement / Prediction**

Intensity (n/s) |	0	− 3e4	3e4	3e4
X, Y (m) |	0, 0	7, 7	7, 7	3, 3
Background (cps) |	3	3	3	3

Expected Impact

Continuing to develop the concept of robotic inspectors for radiation measurements

Improvements to advance particle filtering from a canonical source localization approach to an **application-relevant tool** for remote verification in safeguards and arms control

MTV Impact

Campaigns at **Princeton Plasma Physics Laboratory** to characterize neutron detectors and perform experimental demos

Onsite presentation and discussion with subject matter experts at **Lawrence Livermore National Laboratory**

Conclusions

Successfully adapted the particle filtering framework to perform source localization, absence confirmation, and template matching _without a priori knowledge of the required mode_

Experimentally demonstrated the measurement, interpolation, and matching of a neutron field template

Expanding the repertoire of our N-SpecDir Bot for performing radiation measurements in support of nuclear safeguards and arms control
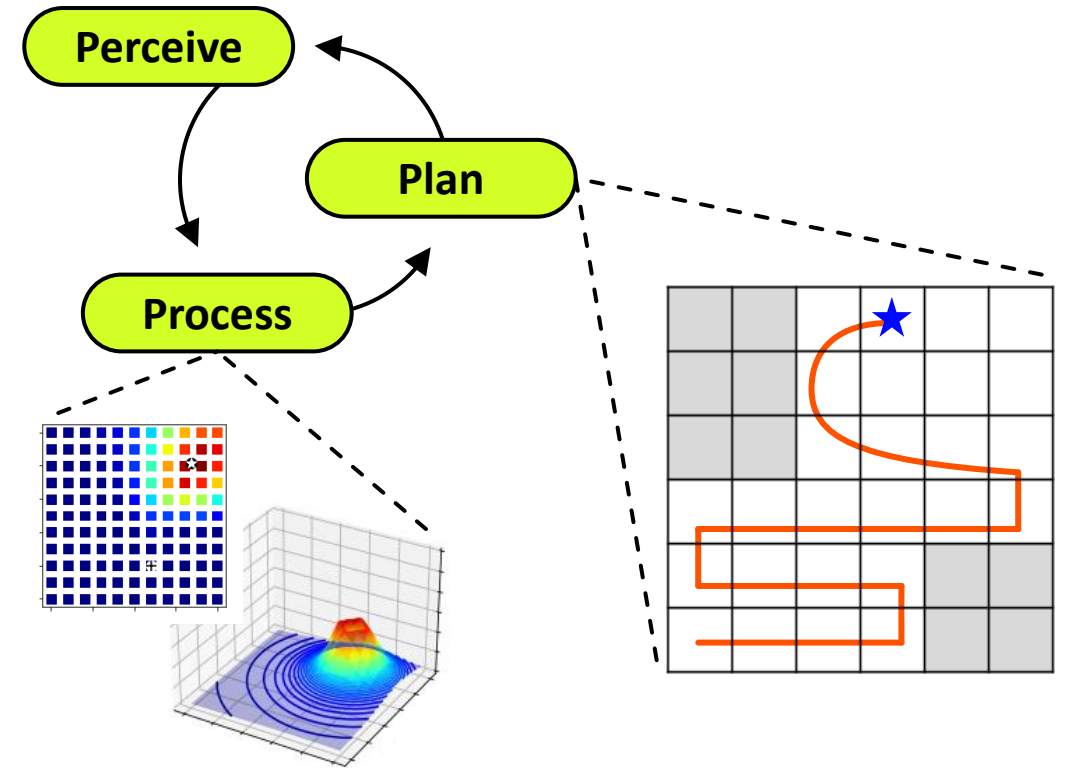
Source Seeking & Motion Planning

Experimentally demonstrate the N-SpecDir Bot's **directionality** for finding a source

[1] with / without **reflection**

[2] with / without the **particle filter**

Path planning and algorithm development for **active sensing** and **absence confirmation**

Contextual Information for Absence

Examining the concept of a **heterogeneous multi-robot system** for characterizing a search area by complementing the N-SpecDir Bot with a **robotic neutron generator**

Concept for absence measurements aided by (light detection & ranging) **LIDAR measurements**
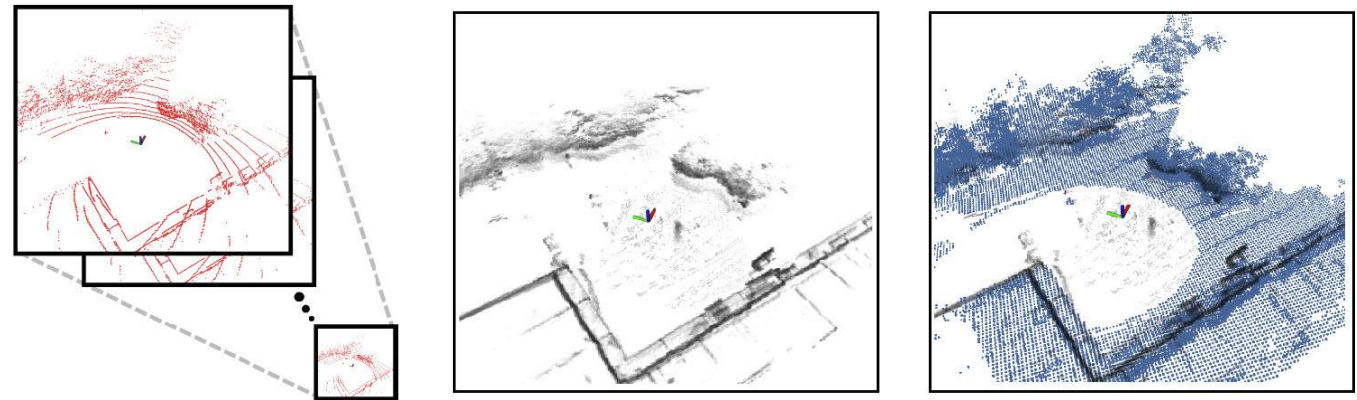

Figure from Ana Batinovic, et. al., *A Multi-Resolution Frontier-Based Planner for Autonomous 3D Exploration*, IEEE Robotics and Automation Letters, Vol. 6, No. 3, July 2021

Acknowledgements

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