Pushing the Bounds of

Minimal-Access Robotic Inspections

with Privacy-Preserving Absence Confirmation

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Introduction & Motivation

Future agreements are likely to require new verification approaches which preserve aspects of onsite inspections while resolving some concerns about intrusiveness

Previously demonstrated the N-SpecDir Bot for single-shot directional determination, source localization, and template matching

with Rob Goldston, PPPL

Mission Relevance

NNSA Mission

Support the implementation of agreements and associated monitoring regimes to verifiably reduce nuclear weapons and programs

Develop strategies to address emerging nonproliferation and arms control challenges and opportunities

Our Contribution

We develop and demonstrate a new remote and autonomous solution for arms control verification

Theoretical guarantees on the privacy and correctness of this approach

Empirically validated by extensive simulated and hardware experiments

Problem Formulation

Assume that a physical, bounded environment is declared (by the host) to contain no radioactive sources

Explore the 2D obstacle-filled space to verify the declaration (or indicate presence, non-compliance)

Minimal sensory input and retention of any observable features (imagery, dimensions, radiation measurements, even the layout)

Exploration & Encoding Algorithm

Absence ↦ robot moves according to a "reference" random walk

Presence ↦ robot moves according to an "out-of-distribution" random walk

Only store the step size between measurements (sufficiently lossy, non-unique filter)

Detect the policy shift by Kolmogorov-Smirnov (KS) testing of the realized action distribution

Algorithm 1 Random walk absence confirmation.

Input: Estimated background B, Outer dimensions l_x, l_y, Confidence parameter p^*, Run time T, Test count n, Threshold level z, Step size constants $0 \leq c_L < c_U$, Reference distribution V_r

Output: Inspection result

Initialize P-value $\underline{p} = 1.0$, Time step $t = 1$, Realized action distribution $\overline{V}_e = \{\emptyset\}$, Starting pose x_0, y_0, θ_0

while $t \leq T$ **do**

  $N_t \sim h(x_t, y_t; E)$ {Field measurement}

  $c \leftarrow c_L + (c_U - c_L)\mathbb{1}[N_t \leq B + z\sqrt{B}]$ {Set max step}

  $ds,\ d\theta \sim \mathcal{U}[0, c],\ \mathcal{U}[0, 2\pi]$ {Step length, rotation}

  Rotate by $d\theta$ rad. and move forward ds distance

  Append ds to memory V_e

  if $t \equiv 0 \pmod{T/n}$ **then**

    $\underline{p} = \min\{\underline{p}, \mathbf{KS}(V_e, V_r)\}$ {Perform KS test}

  end if

  if $\underline{p} \leq p^*/n$ **then**

    return 1 {Result: Anomaly detected}

  end if

end while

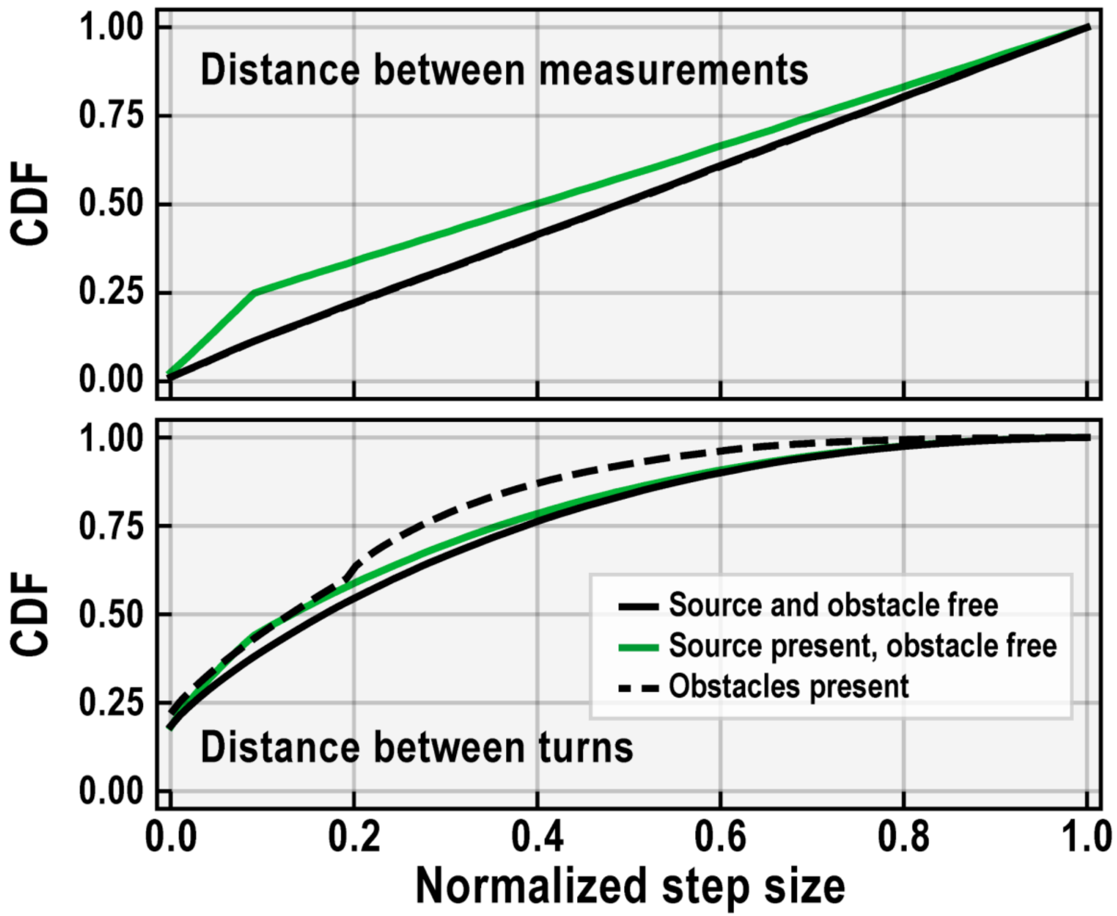
return 0 {Result: Absence confirmed}

Provable Privacy

All source-free maps result in the exact same action distribution

$$\mathcal{MI}(\{\mathcal{G}_t \backslash \mathcal{G}_{t-1}\}, \mathbb{M}^-) = 0 \; \forall t \geq 1$$

Cannot distinguish between any pair of source-free (compliant) maps using the information encoding & storage scheme



Guaranteed Correctness

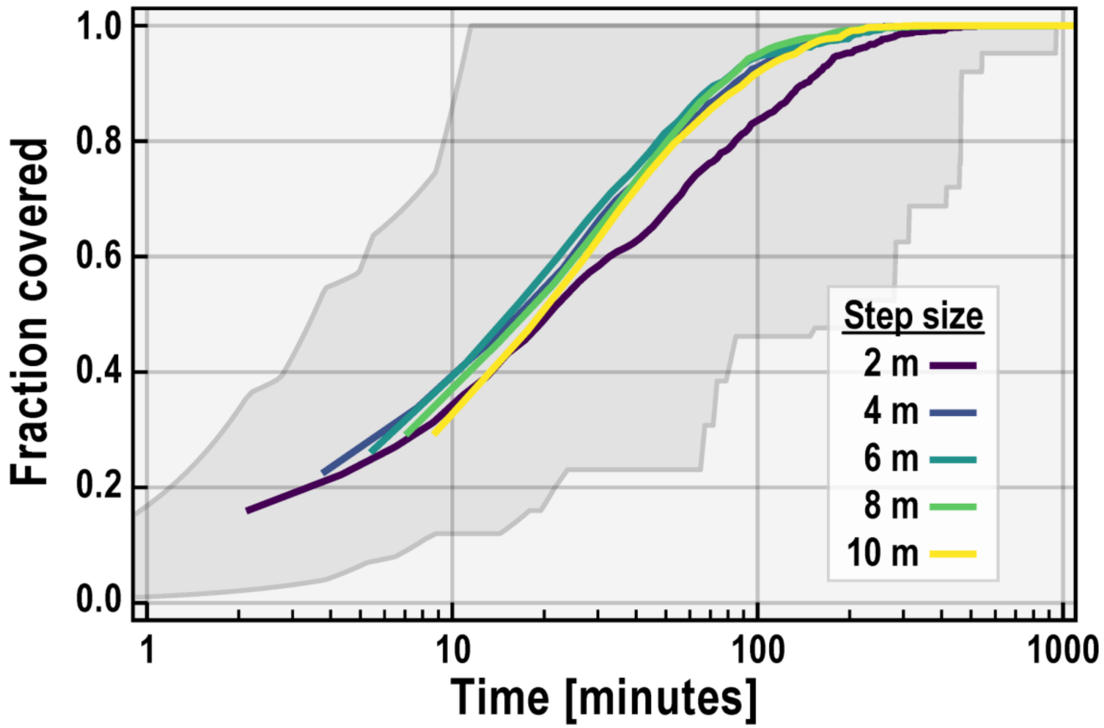
High-confidence distribution testing

limit false-positives

High-probability environment coverage

limit false-negatives

**assumes that sources are detectable if the robot is sufficiently close*



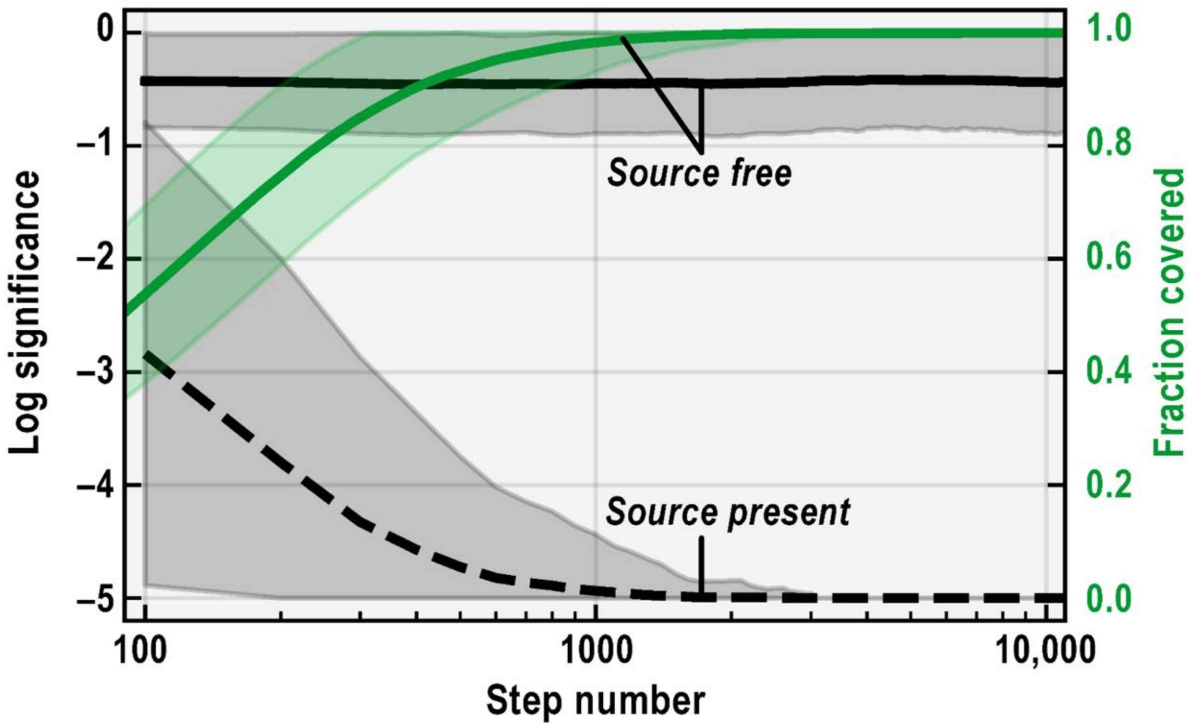
10 x 10 m environments
3-second measurements, 10 cm/s travel speed

Simulated Demo

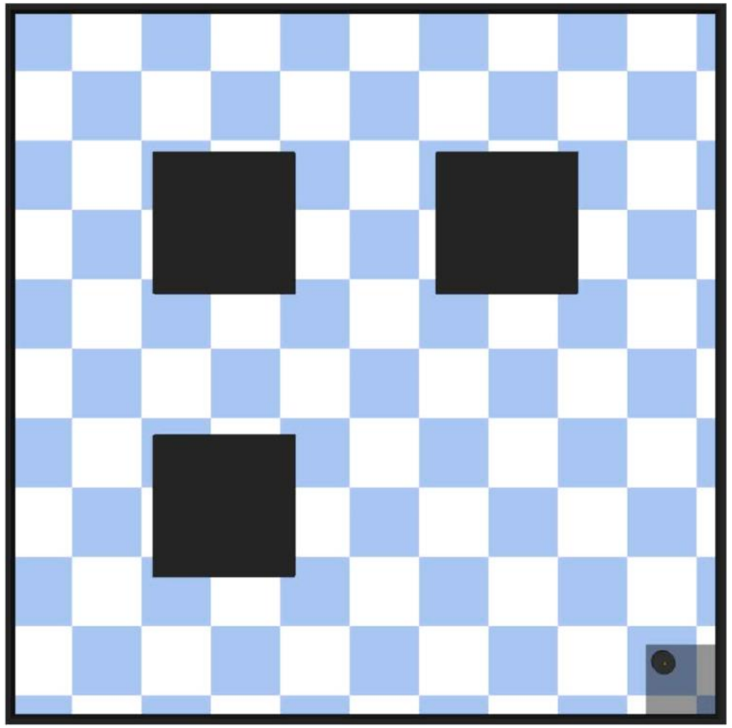
30 environments simulated in PyBullet
Laboratory-based radiation measurement model
100 trials per map (50 absence, 50 presence)
99.5% confidence inspection result

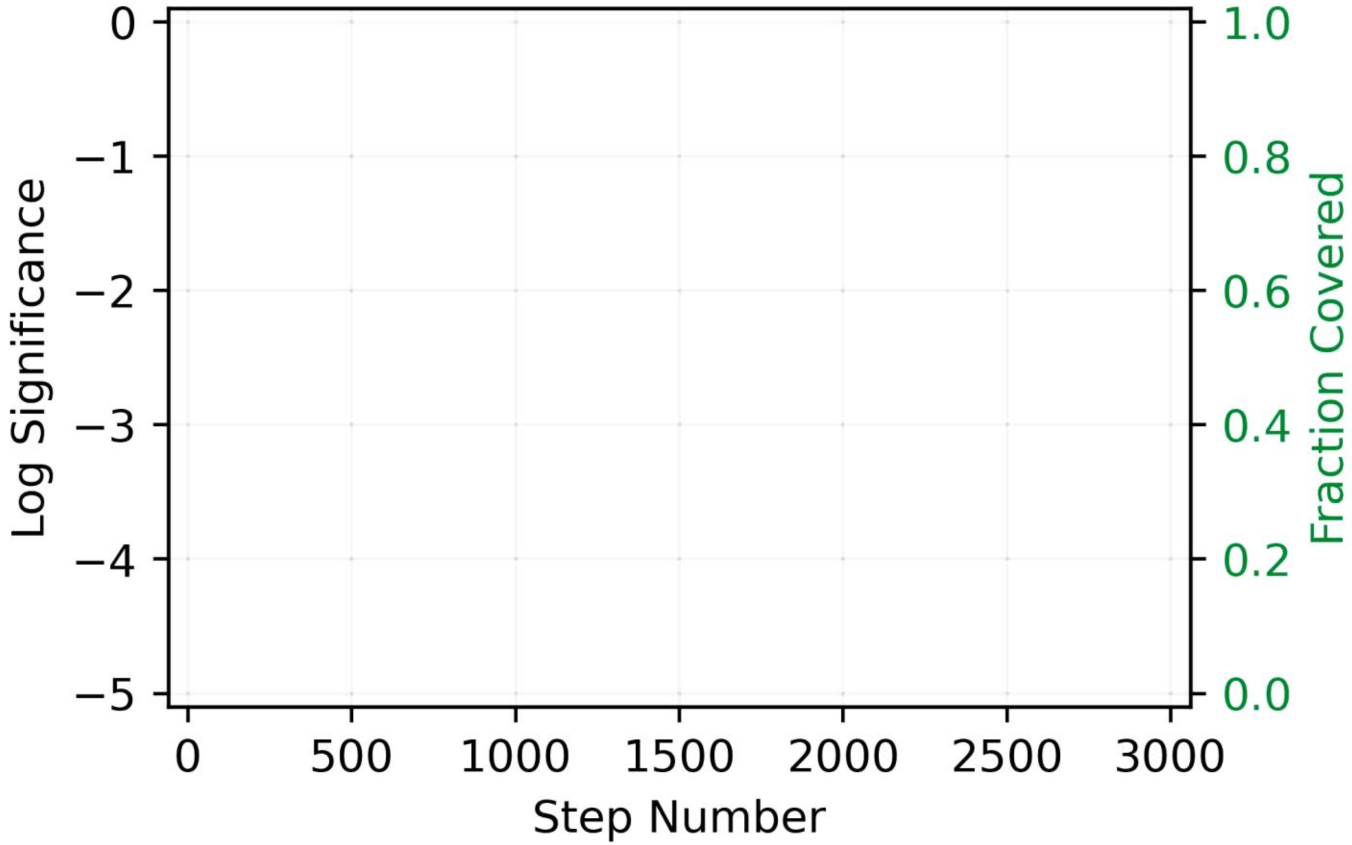
“Anomaly detected”
KS test log significance reaches threshold
$log(P) = -5$

“Absence confirmed”
Coverage is achieved (with high probability) without a significant KS test

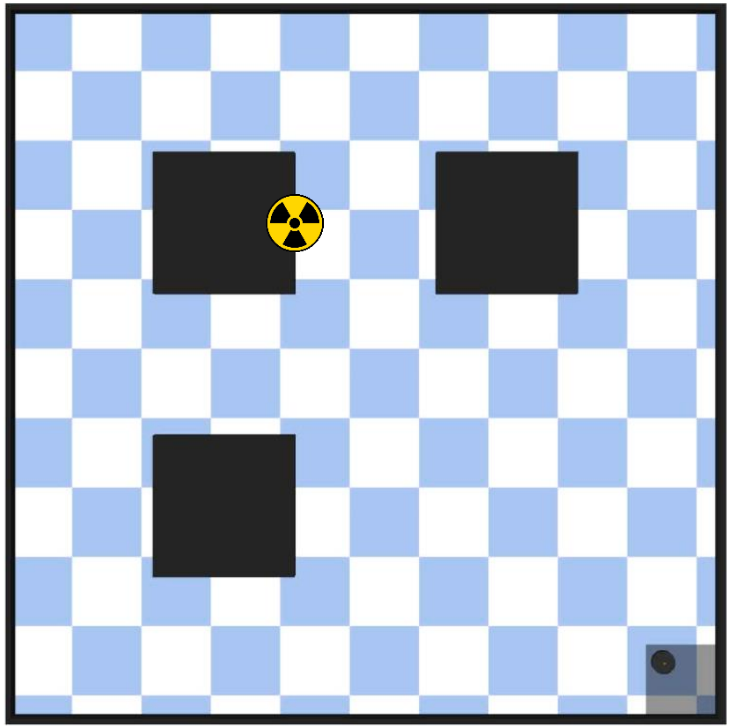


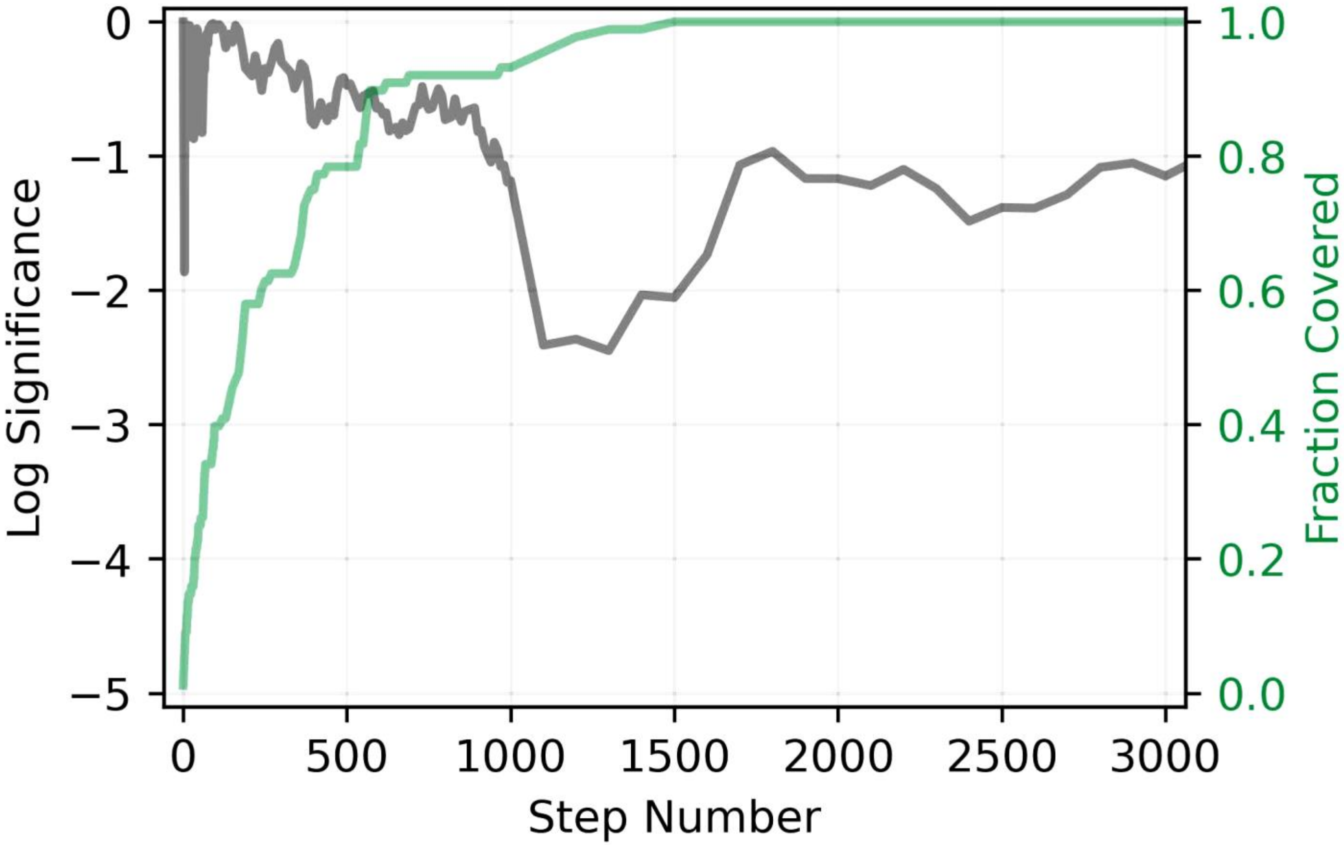
Simulated Demo – Absence



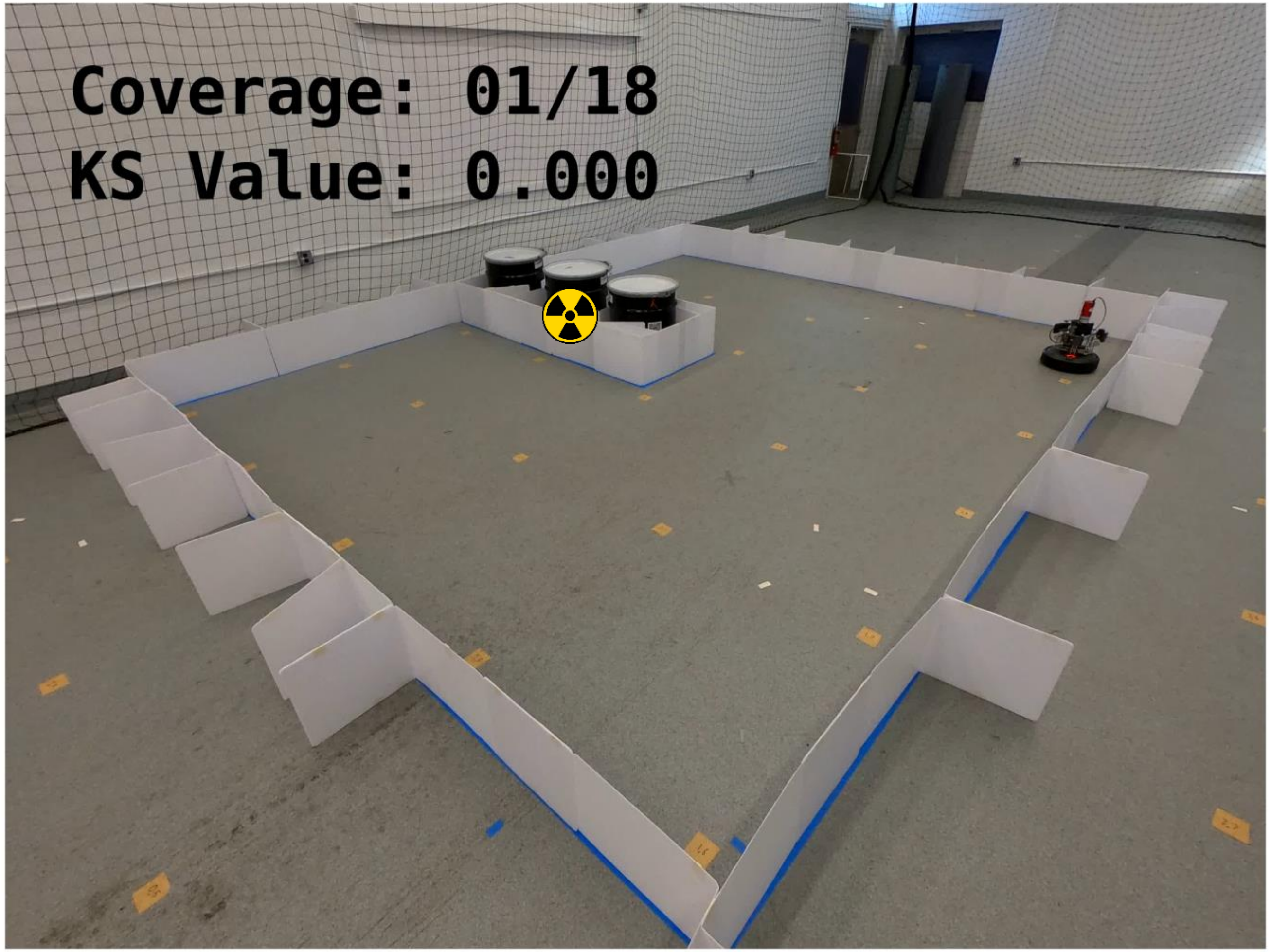


Simulated Demo – Presence





Hardware Demo – Presence



Sensing-agnostic algorithm compatible with any robotic radiation detector

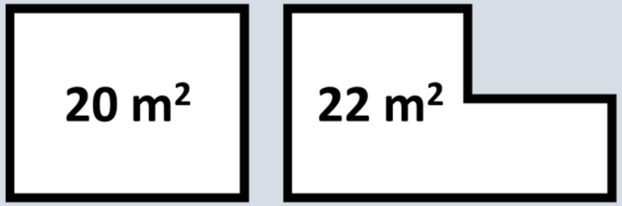
iRobot Create 3 robotic platform

- LND 7314 2in Pancake Geiger detector (×3) (same as Safecast bGeigie Nano)
  - *Adafruit ESP32 Feather V2*
- 2-inch Mirion/Canberra NaI scintillator (Model 802) & Osprey Digital MCA Tube Base
  - *Raspberry Pi 4 Model B*

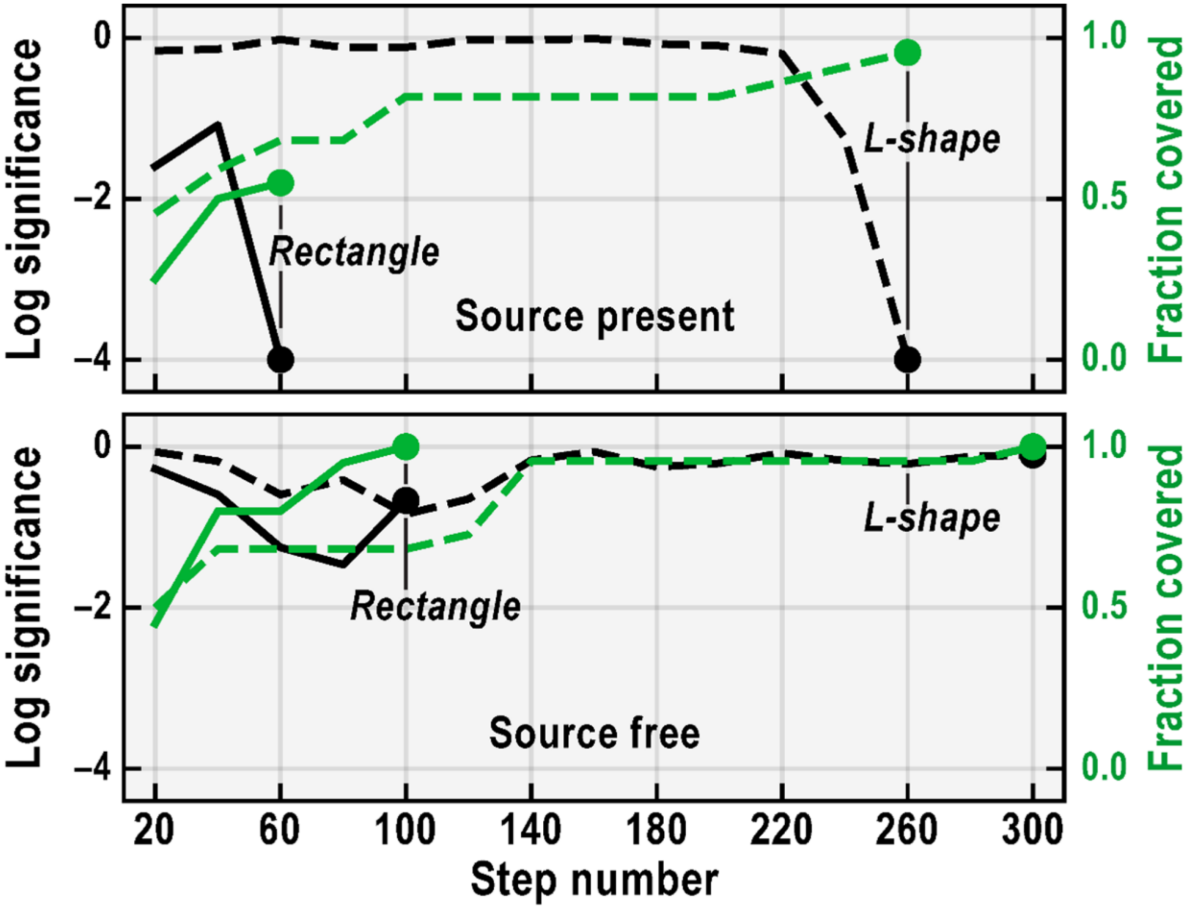
Vicon V16 mo-cap cameras used for omniscient coverage tracking

- *Courtesy of Intelligent Robot Motion Lab*

Hardware Demo



Full-scale
KS test and
coverage



Expected Impact & MTV Impact

Highlights a trade-off between permissible information and inspection efficiency & efficacy

By considering an exceedingly strict information constraint, we hope to contribute to a dialogue on what may be possible in the future

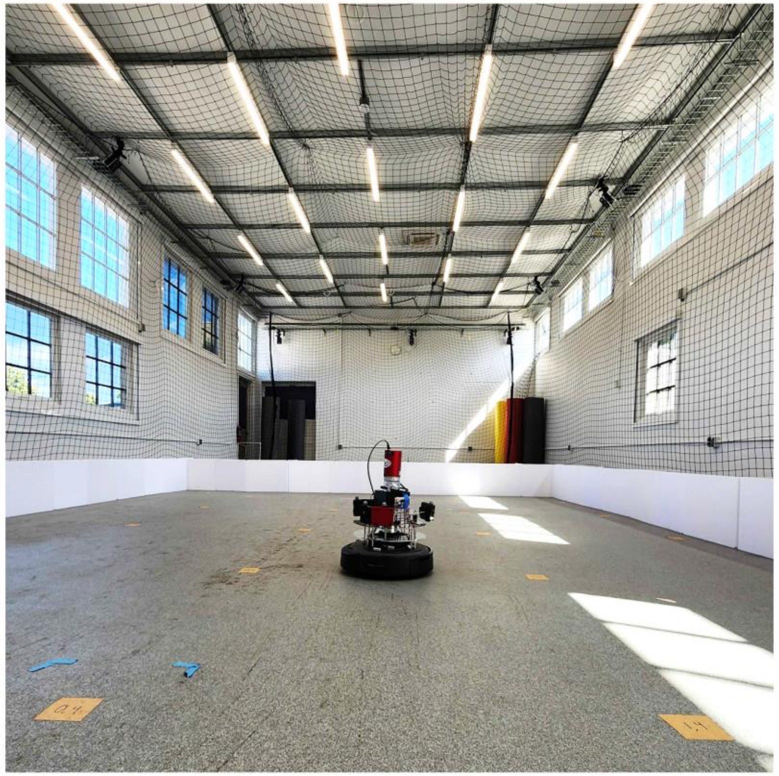
Opportunity to “field-test” our approach at 2023 International Conference on Robotics and Automation (ICRA) Workshop on Bridging the Lab-to-Real Gap

Prior work (**N-SpecDir Bot**) with Rob Goldston, PPPL

Conclusions & Next Steps

Applying robotics to radiation detection from an information theoretic perspective

Demonstrated the plausibility of a minimal-information verification task with provable-privacy and calibrated-correctness



If verification remains possible even in the limit of no observational information, **what else is possible?**

Continued interest in exploring “minimal access” approaches for verification

Acknowledgements

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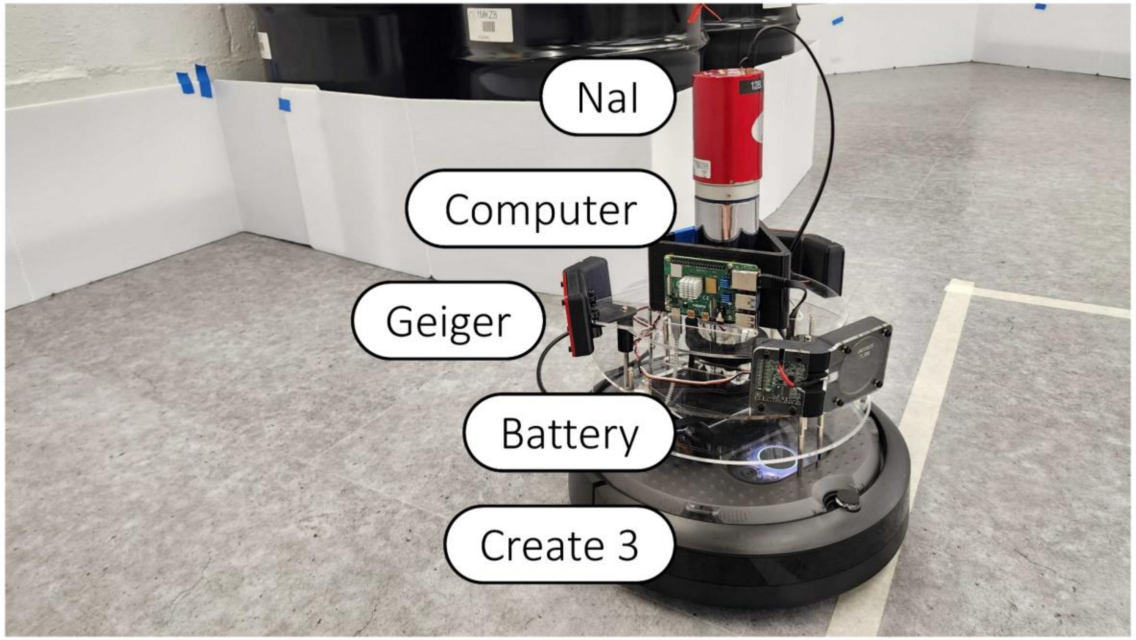
Hardware Demo



NaI detector binning provides 2.54-times faster coverage

Geiger counters require 3.33-times more steps to reach KS test threshold

Advantageous to use higher efficiency detectors