ROBOTIC & REMOTE INSPECTIONS

FOR NUCLEAR SAFEGUARDS, VERIFICATION, AND BEYOND

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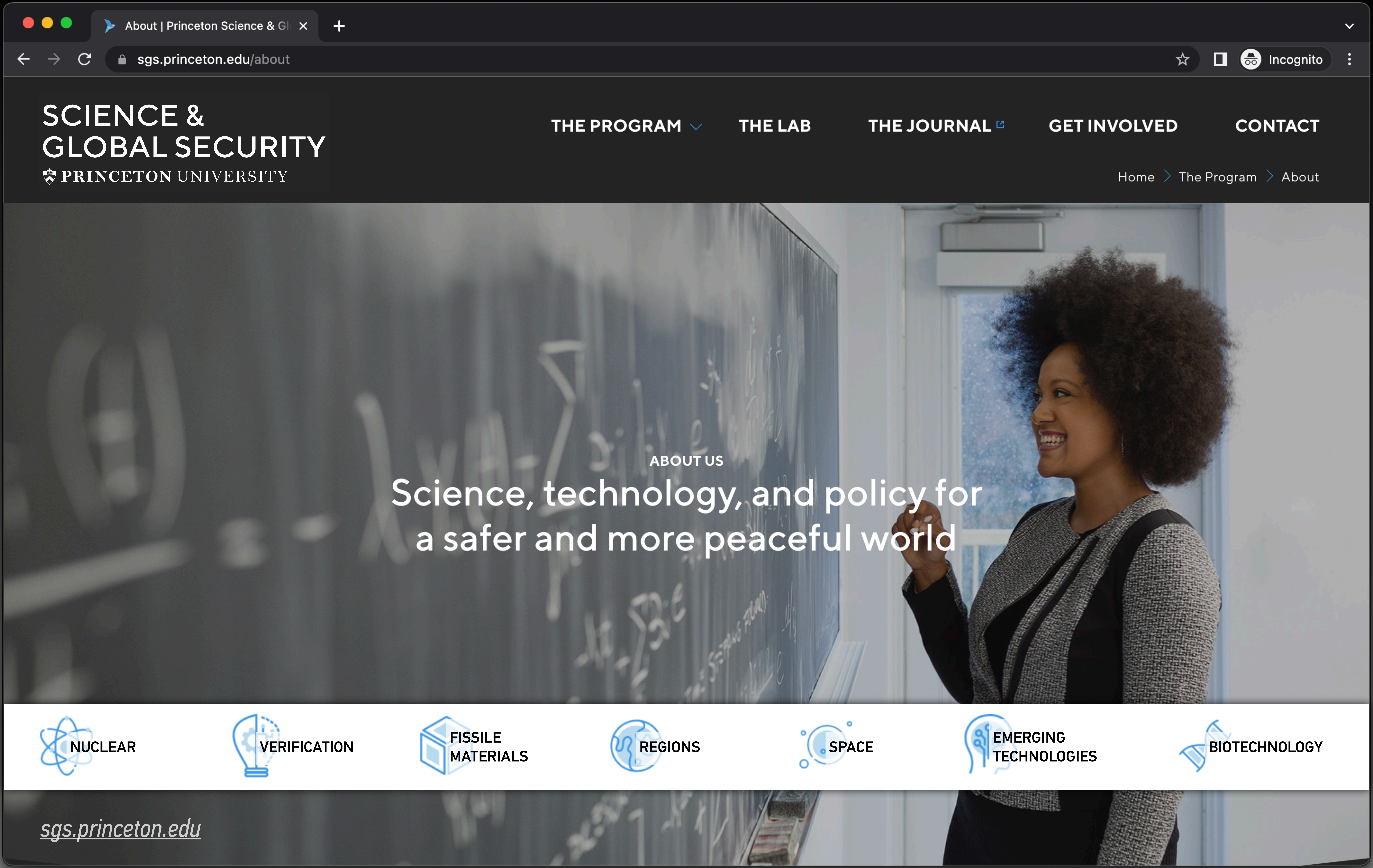
Revision 0.4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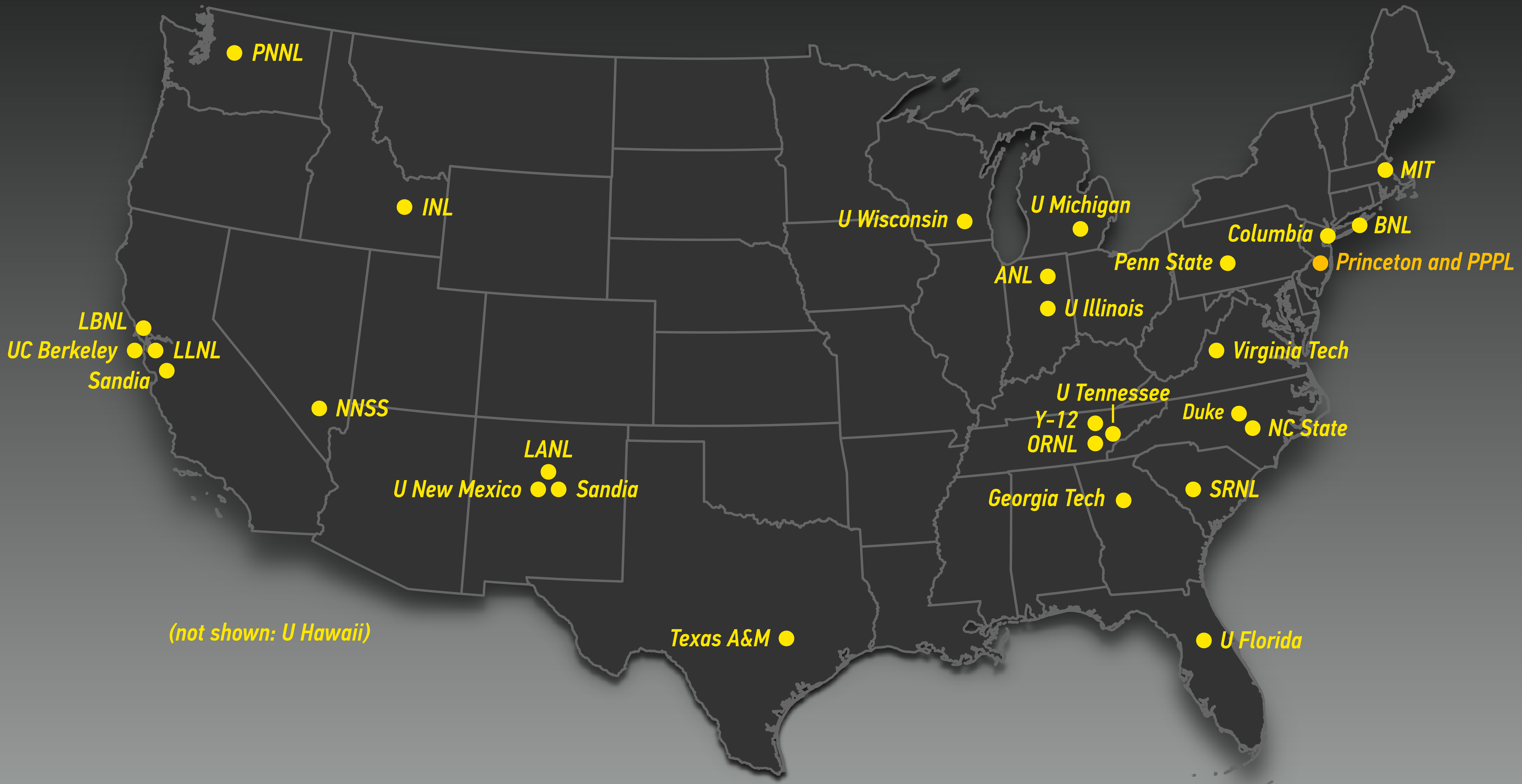
CONSORTIUM FOR MONITORING, TECHNOLOGY, AND VERIFICATION (MTV)



Five-year project, funded by U.S. DOE, 14 U.S. universities and 13 national labs, led by U-MICH

ROBOTS IN HUMAN ECOLOGY

A HANDS-ON COURSE FOR ANTHROPOLOGISTS, ENGINEERS, AND POLICYMAKERS

ANT 325 / MAE 347 / SPI 384 (Spring 2024)

sgs.princeton.edu/robots-human-ecology

Why would one consider robotic & remote inspections?

FROM ONSITE TO REMOTE INSPECTIONS

PROS & CONS OF ONSITE INSPECTIONS

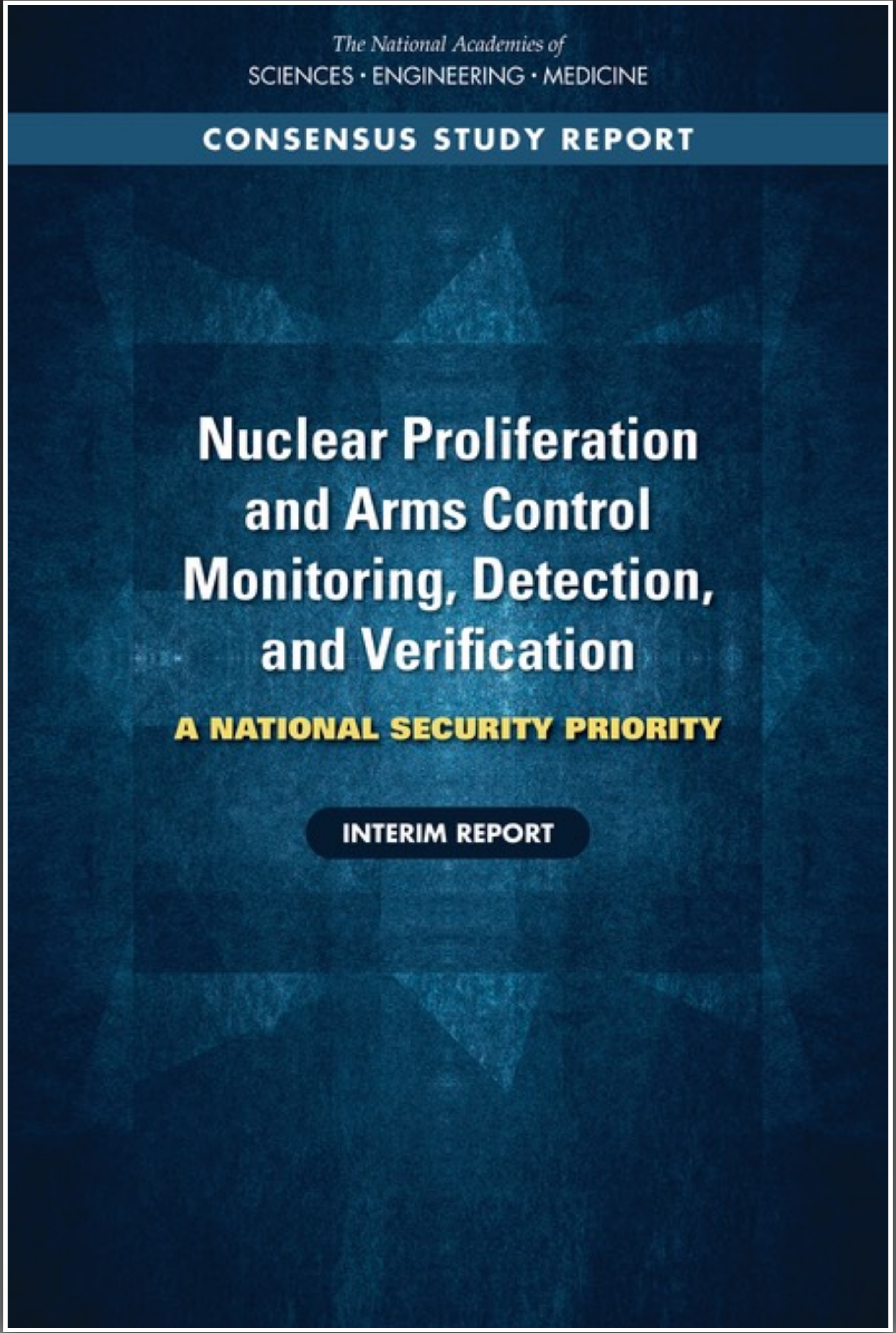
Onsite inspections remain the "gold standard" for IAEA safeguards and nuclear arms-control verification; inspections tend to be costly and are often considered intrusive, especially in the arms-control context

CAN WE (PHYSICALLY) "SEPARATE" HOST & INSPECTOR?

Many concerns could be addressed and resolved if inspectors were not "physically" present onsite; we are exploring various approaches to remote inspections with a particular emphasis on robotic inspections

Source: ukni.info (top) and microsoft.com (bottom)

FINDINGS FROM A 2021 NATIONAL ACADEMIES STUDY



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).*

Jill Hruby, Corey Hinderstein, et al., Committee on the Review of Capabilities for Detection, Verification, and Monitoring of Nuclear Weapons and Fissile Material, National Academy of Sciences, Washington, DC, 2021, doi.org/10.17226/26088

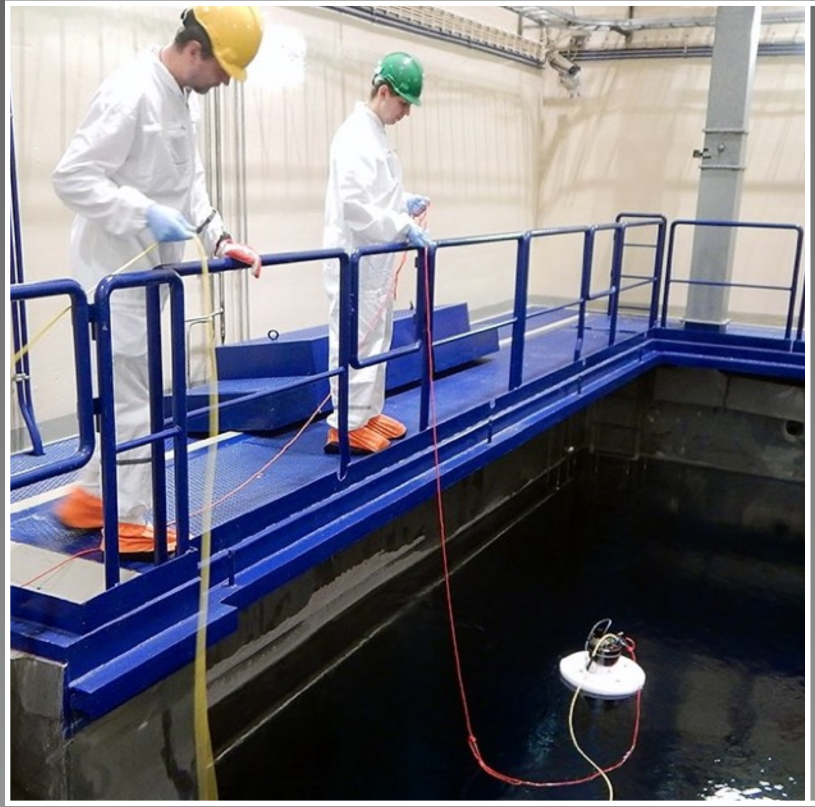
ROBOTIC INSPECTIONS


(not the actual ROBIN)

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."

www.iaea.org/topics/safeguards-in-practice/robotics-challenge-2017

Source: SRI International (Shakey, 1966–1972, top) and IAEA (bottom)

NUCLEAR SAFEGUARDS & ARMS CONTROL

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

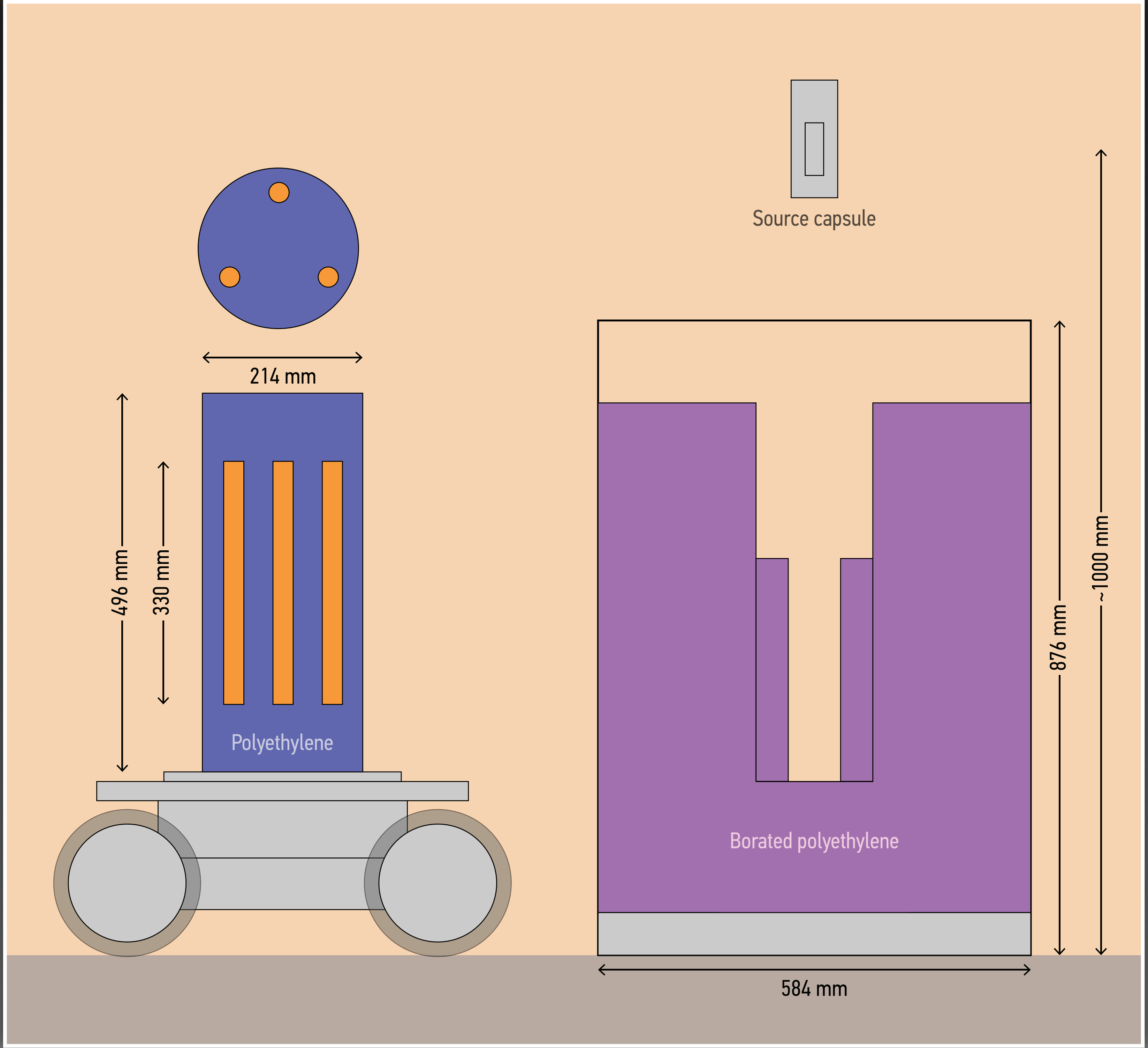
Confirming that a neutron field in a storage facility remains unchanged

- Robot should not "learn" or "remember" measurement data
- Robot only reports simple, non-sensitive inspection results (pass/fail)

Source: president.ir (top) and commons.wikimedia.org (D5481026, bottom)

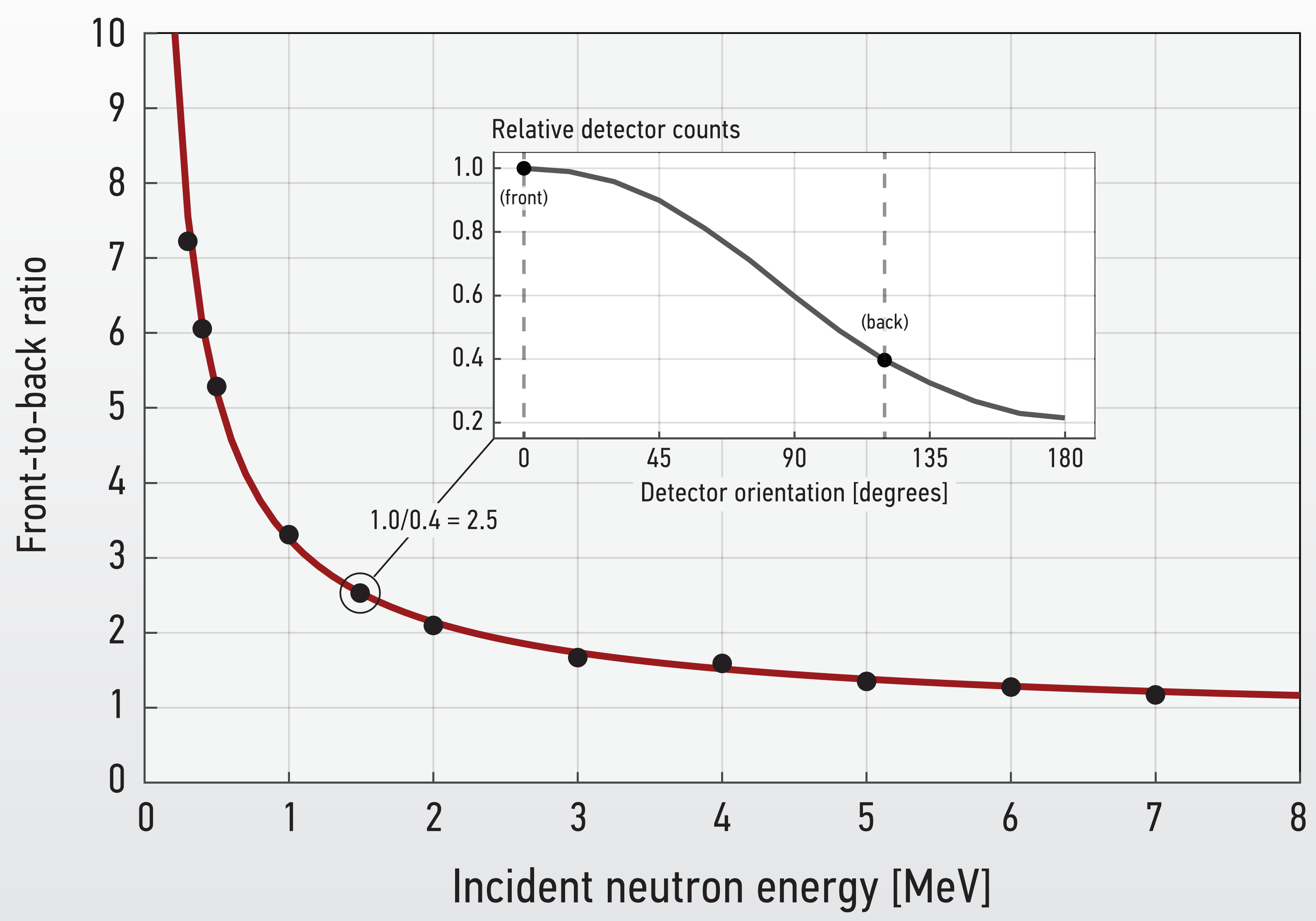
Some Examples

INSPECTOR BOT @ PPPL

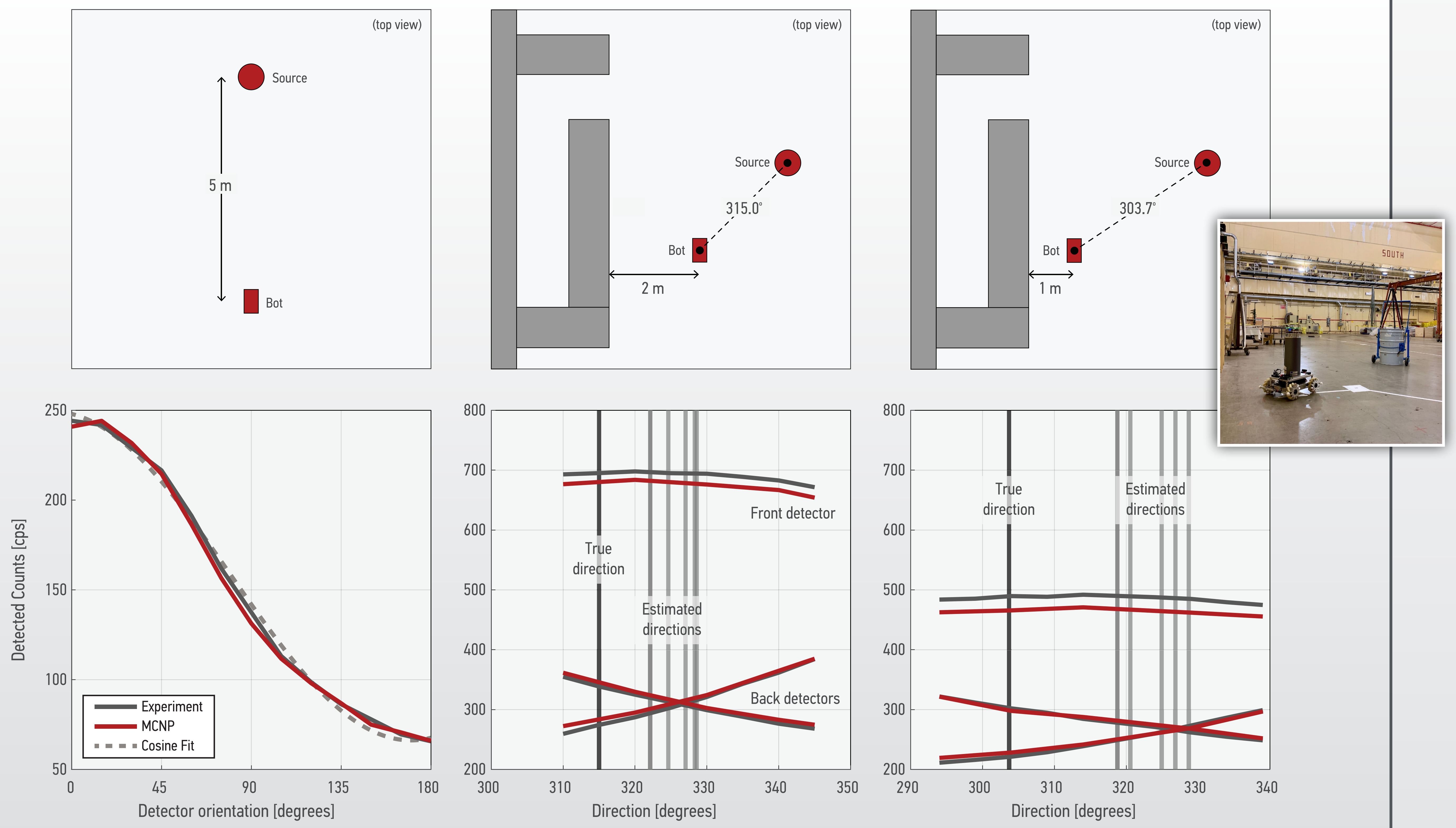


Boron-coated straw (BCS) detectors embedded in a polyethylene cylinder
One 3-detector (pictured) and two 6-detector systems available
Method for “single-shot” directional measurements; experimentally-benchmarked MCNP model

SPECTRAL & DIRECTIONAL SENSITIVITY



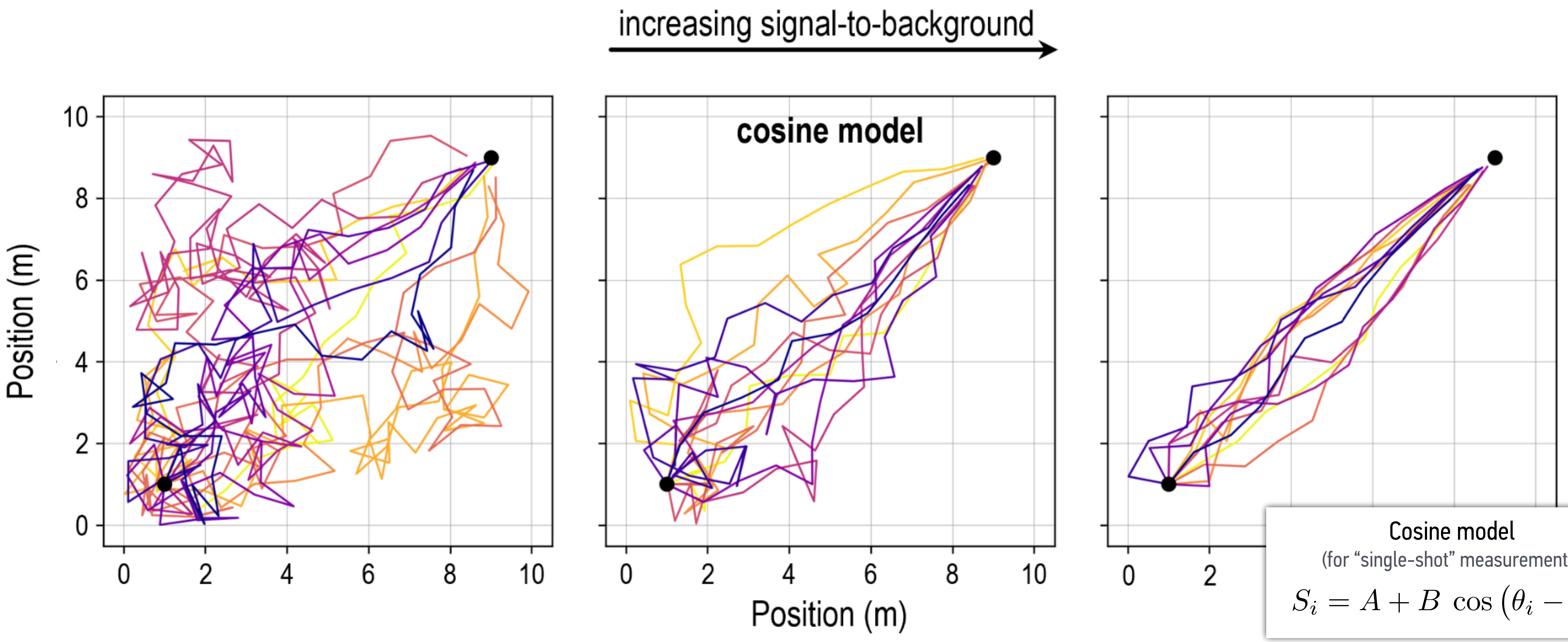
Front-to-back ratio indicative of
the (average) energy of incident neutrons



E. Lepowsky, M. Kütt, S. Aslam, H. Fetsch, S. Snell, A. Glaser, and R. J. Goldston, “Experimental Demonstration and Modeling of a Robotic Neutron Detector with Spectral and Directional Sensitivity for Treaty Verification,” *Nuclear Instruments and Methods in Physics Research A,* August 2022

LOCALIZING AN UNKNOWN SOURCE

BIASED RANDOM WALK EXAMPLES USING A DIRECTIONAL RADIATION DETECTOR

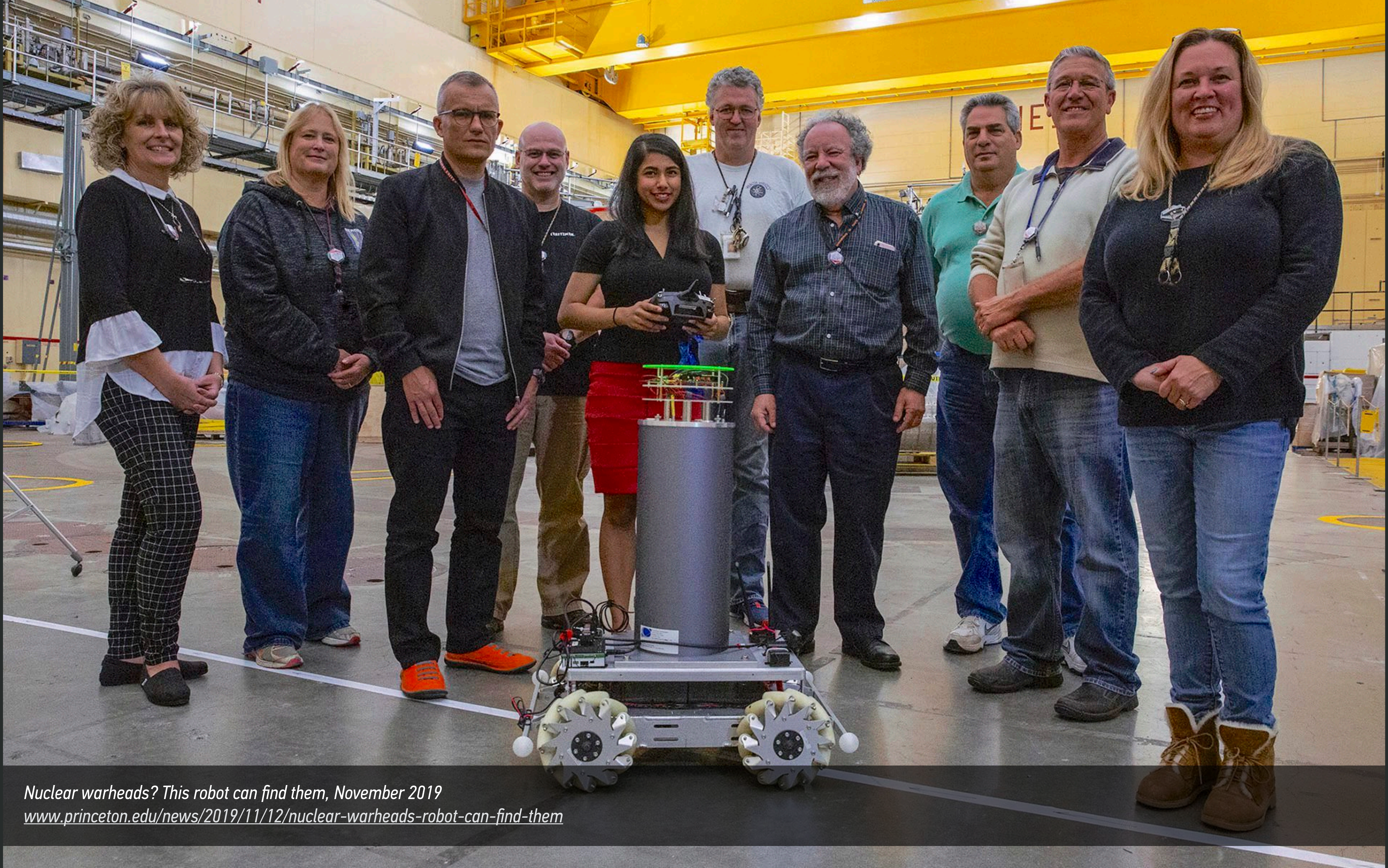


Cosine model

(for "single-shot" measurements)

$$S_i = A + B\ \cos\left(\theta_i - \theta_0\right)$$

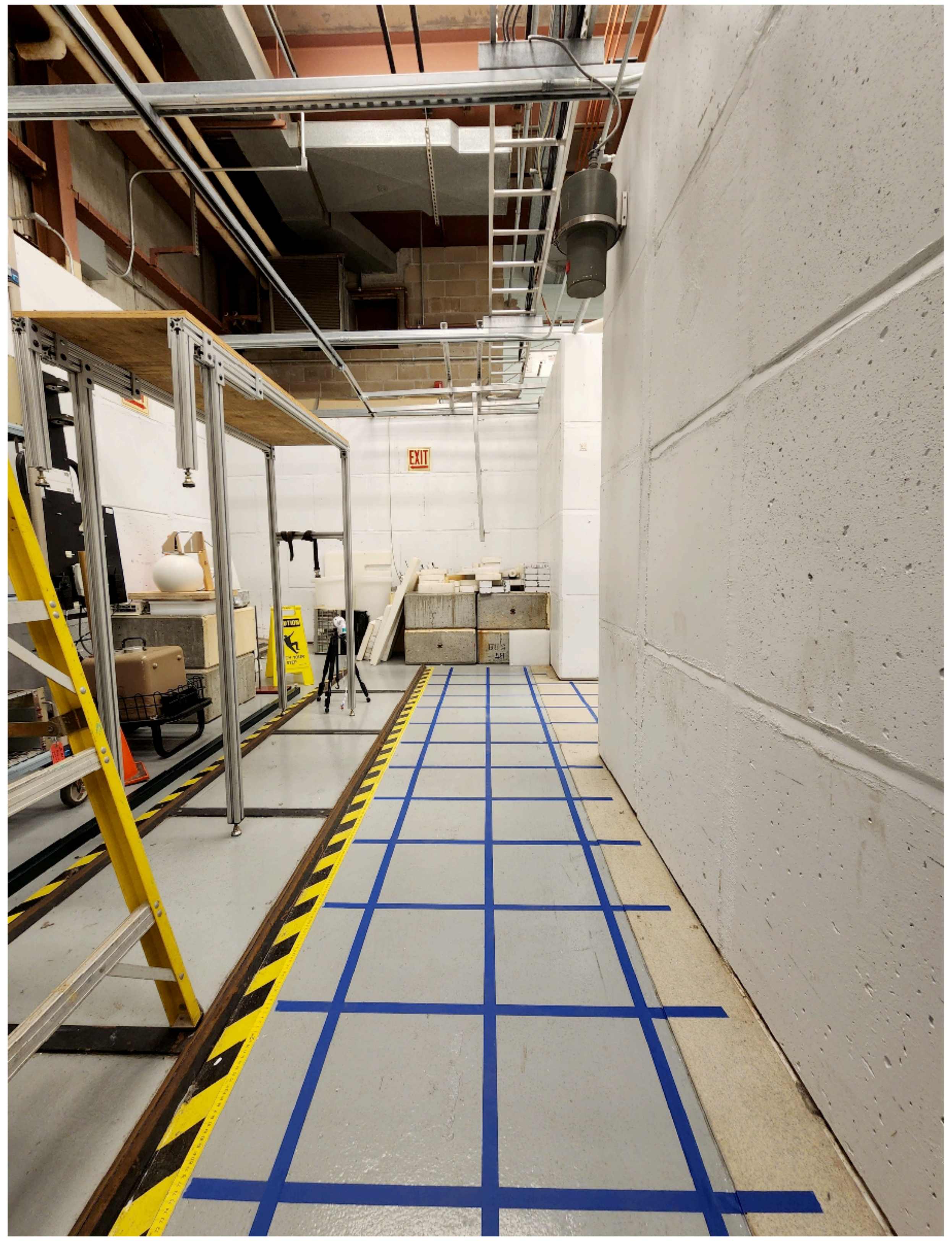
Eric Lepowsky, Absent-Minded and Robotic Inspectors: Nuclear Verification Techniques with Minimal Access to Items, Sites, and Information, PhD Thesis, Princeton University, May 2024



Nuclear warheads? This robot can find them, November 2019
www.princeton.edu/news/2019/11/12/nuclear-warheads-robot-can-find-them

LOCALIZING AN UNKNOWN SOURCE

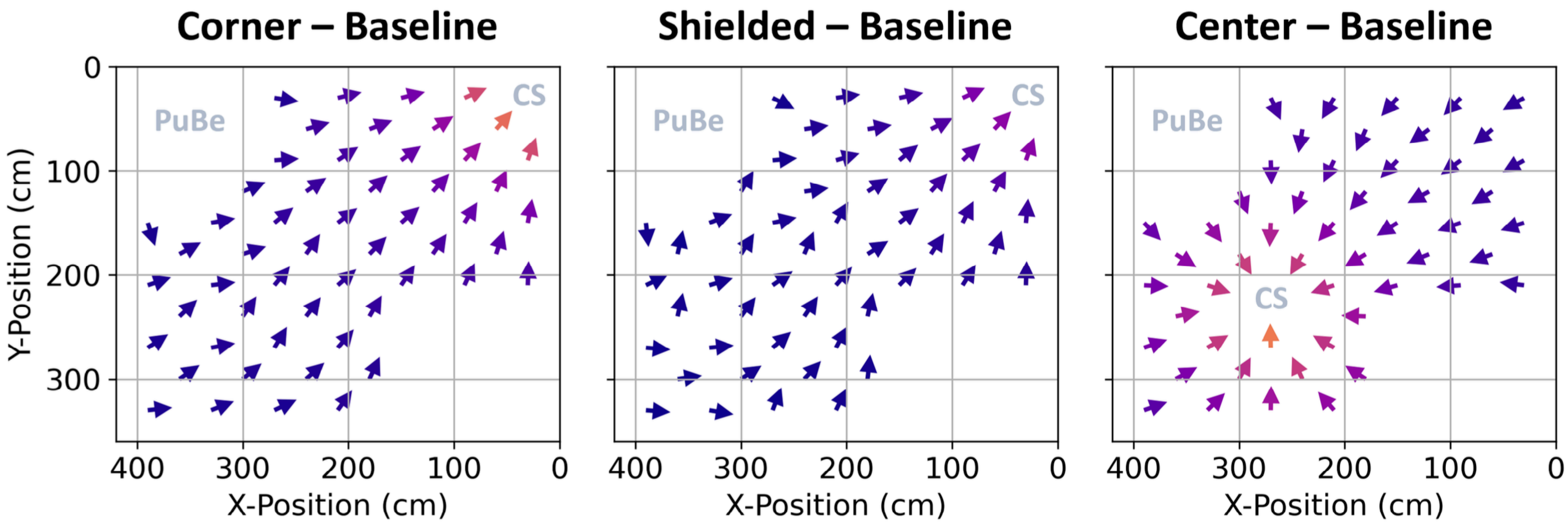
IN THE PRESENCE OF AN EXISTING NEUTRON FIELD



Field Measurements in PPPL's Calibration and Service Laboratory (CASL), led by Eric Lepowsky

LOCALIZING AN UNKNOWN SOURCE

IN THE PRESENCE OF AN EXISTING NEUTRON FIELD (USING THE TEMPLATE METHOD)

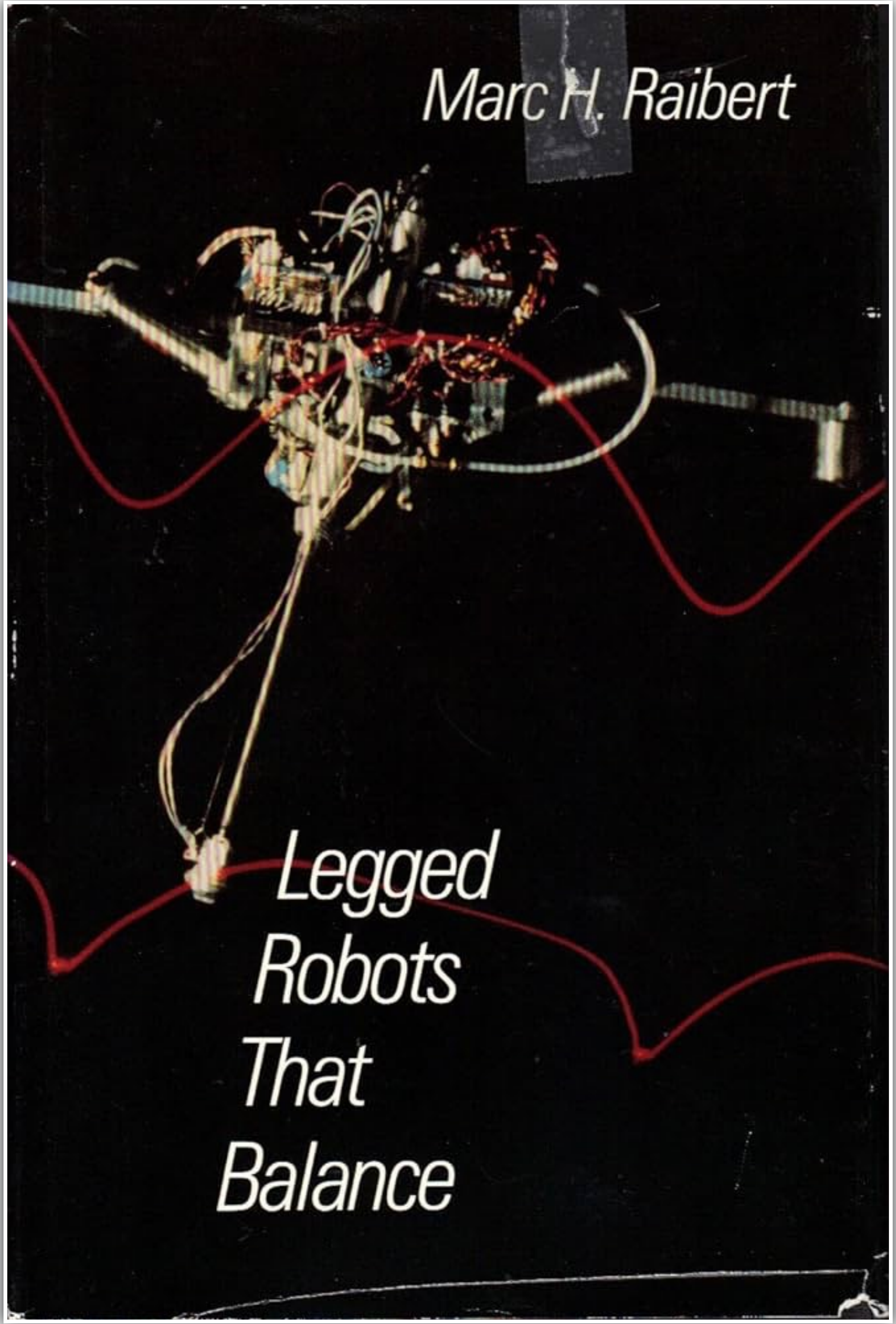


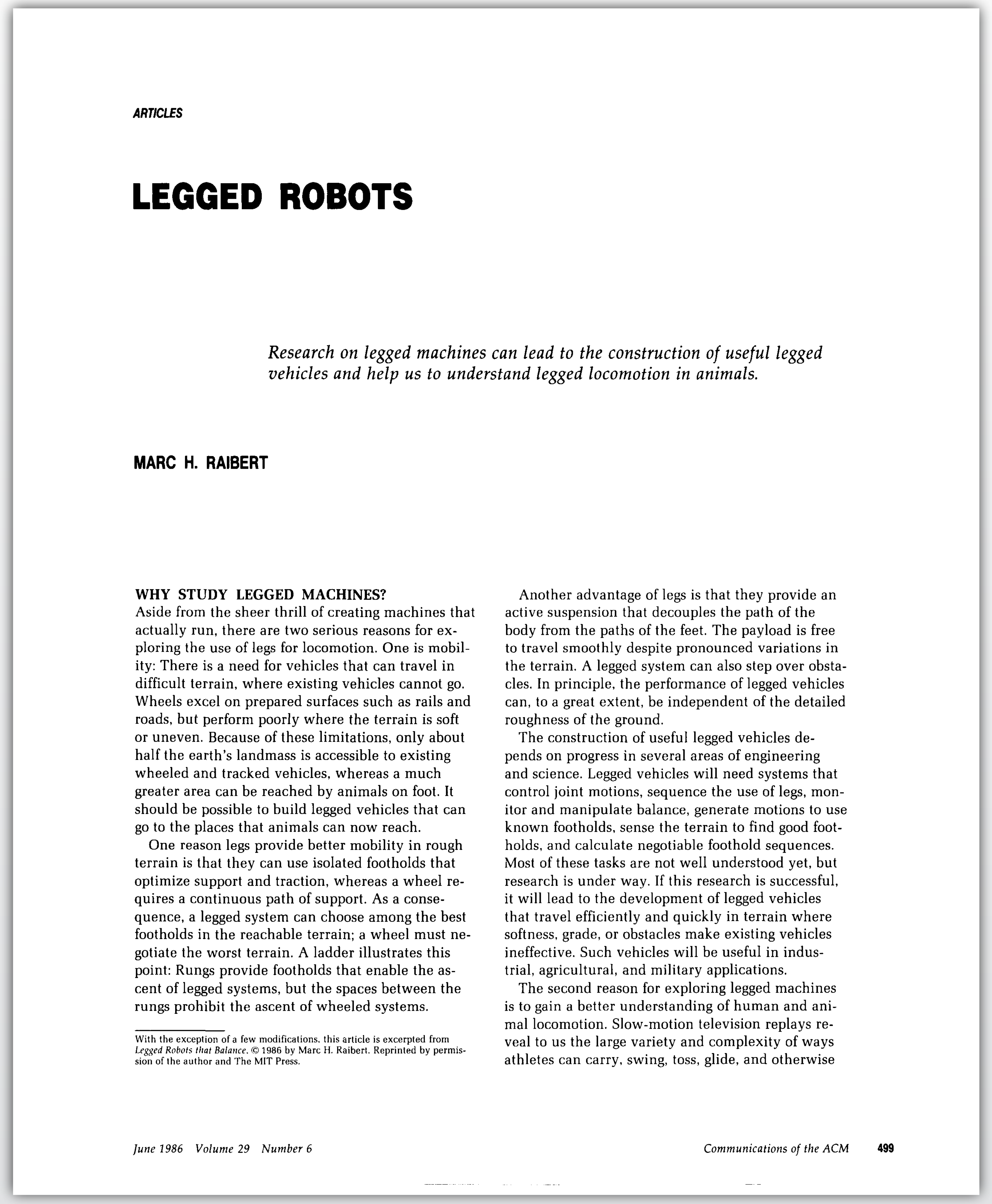
Eric Lepowsky, Absent-Minded and Robotic Inspectors: Nuclear Verification Techniques with Minimal Access to Items, Sites, and Information, PhD Thesis, Princeton University, May 2024

Source: Boston Dynamics

SPOT's anatomy and its basic features

LEGGED ROBOTS





ARTICLES

LEGGED ROBOTS

Research on legged machines can lead to the construction of useful legged vehicles and help us to understand legged locomotion in animals.

MARC H. RAIBERT

WHY STUDY LEGGED MACHINES?
Aside from the sheer thrill of creating machines that actually run, there are two serious reasons for exploring the use of legs for locomotion. One is mobility: There is a need for vehicles that can travel in difficult terrain, where existing vehicles cannot go. Wheels excel on prepared surfaces such as rails and roads, but perform poorly where the terrain is soft or uneven. Because of these limitations, only about half the earth's landmass is accessible to existing wheeled and tracked vehicles, whereas a much greater area can be reached by animals on foot. It should be possible to build legged vehicles that can go to the places that animals can now reach.

One reason legs provide better mobility in rough terrain is that they can use isolated footholds that optimize support and traction, whereas a wheel requires a continuous path of support. As a consequence, a legged system can choose among the best footholds in the reachable terrain; a wheel must negotiate the worst terrain. A ladder illustrates this point: Rungs provide footholds that enable the ascent of legged systems, but the spaces between the rungs prohibit the ascent of wheeled systems.

Another advantage of legs is that they provide an active suspension that decouples the path of the body from the paths of the feet. The payload is free to travel smoothly despite pronounced variations in the terrain. A legged system can also step over obstacles. In principle, the performance of legged vehicles can, to a great extent, be independent of the detailed roughness of the ground.

The construction of useful legged vehicles depends on progress in several areas of engineering and science. Legged vehicles will need systems that control joint motions, sequence the use of legs, monitor and manipulate balance, generate motions to use known footholds, sense the terrain to find good footholds, and calculate negotiable foothold sequences. Most of these tasks are not well understood yet, but research is under way. If this research is successful, it will lead to the development of legged vehicles that travel efficiently and quickly in terrain where softness, grade, or obstacles make existing vehicles ineffective. Such vehicles will be useful in industrial, agricultural, and military applications.

The second reason for exploring legged machines is to gain a better understanding of human and animal locomotion. Slow-motion television replays reveal to us the large variety and complexity of ways athletes can carry, swing, toss, glide, and otherwise

With the exception of a few modifications, this article is excerpted from *Legged Robots that Balance*. © 1986 by Marc H. Raibert. Reprinted by permission of the author and The MIT Press.

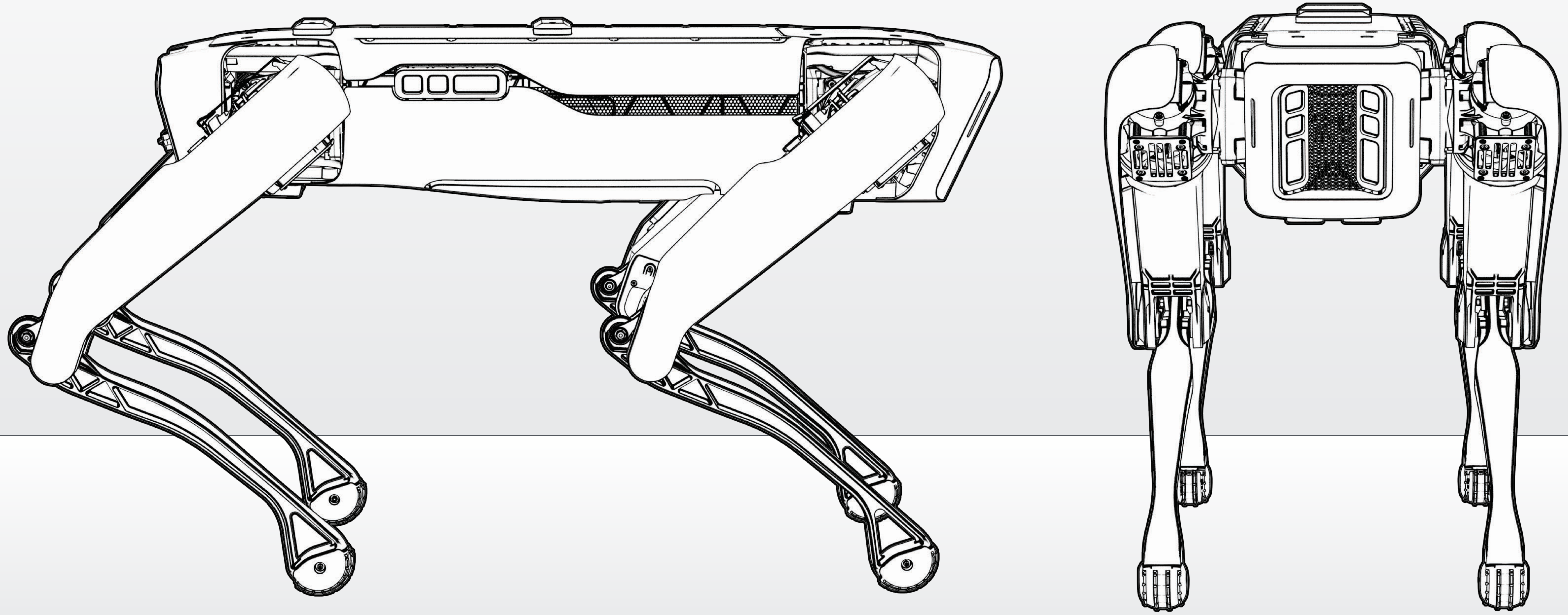
June 1986 Volume 29 Number 6 *Communications of the ACM* **499**

Quadruped (1984–1987)

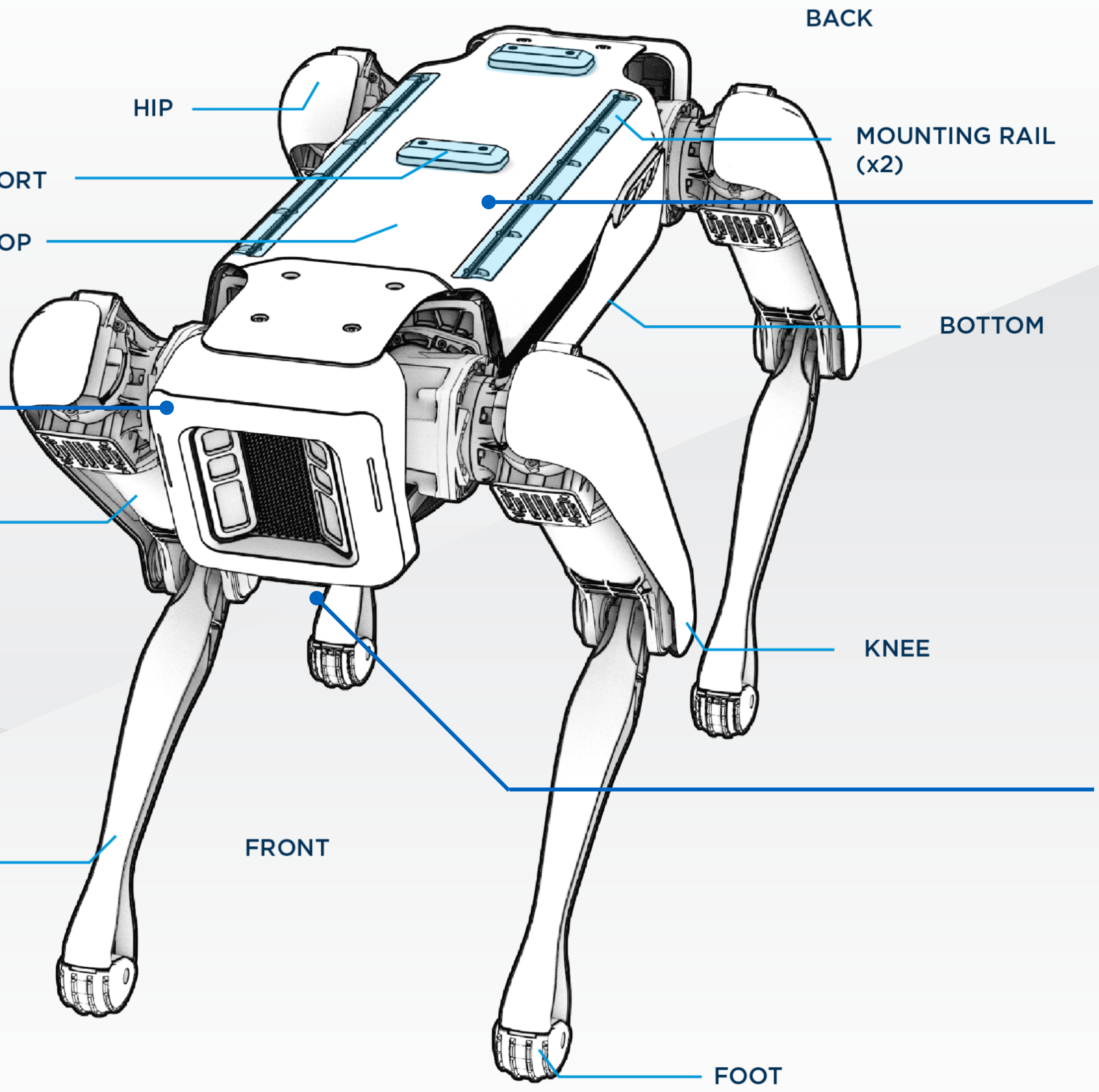
Marc H. Raibert, "Legged Robots," *Communications of the ACM,* 29 (6), June 1986, dl.acm.org/doi/10.1145/5948.5950

MIT Leg Laboratory (founded in 1980), www.ai.mit.edu/projects/leglab

SPOT'S ANATOMY



dev.bostondynamics.com/docs/concepts/about_spot



5 pairs pairs of stereo cameras that provide black and white images and video

Payloads currently available at Princeton: robot arm with gripper, which is permanently installed; the Spot Enhanced Autonomy Payload (EAP2), with a LIDAR sensor, a GPU, and 5G/LTE connectivity

The latest revision of the robot ("SPOT AV") adds audiovisual feedback for users and bystanders, indicating the status and "intentions" of SPOT

dev.bostondynamics.com/docs/concepts/about_spot

"SPOT AV"

Color	Pattern	Buzzer	Robot status	Example
Green	Slow blink[1]	Off	Normal operations, motor power ON.	Most locomotion during manual and automatic operation.
	Fast blink[2]	Off	Normal operations, while starting or changing motion.	Docking and undocking.
	Pulse[3] (front indicator off)	Off	Normal operations, waiting for an automated response (not for human intervention).	Waiting to regain sufficient clearance with respect to other moving objects along or near Spot's path during automatic operation.[4]
Amber	Slow blink[1]	Slow beep[1]	Normal operations with an increased level of warning.	Traversing a crosswalk area during automatic operation.[4]
	Fast blink[2]	Fast beep[2]	Normal operations, before starting activities with an increased level of warning.	About to traverse a crosswalk area during automatic operation.[4]
	Flash[5] (front indicator off)	Slow beep[1]	Normal operations with an increased level of warning (special cases).	Traversing stairs.
	Solid	Off	Activation of safety response.	Motors powering off as a result of an operator command or protective stop.
Red	Fast blink[2]	Off	Failure or emergency situation.	Emergency Stop pressed, or safety input interface not properly configured.
White	Pulse[3]	Off	Normal operations, waiting for human intervention or during processes of variable length.	No or minimal apparent motion while capturing sensor data during automatic operation.

SPOT'S OBSTACLE AVOIDANCE

Perception Features

- General obstacle avoidance
- Walk on grated floor
- Descend stairs before power off
- Ground height detection
- Stairs/surface edge avoidance
- Avoid negative obstacles
- Autowalk "Avoid Ground Clutter"

Limitations

- Glass, mirror, or bright obstacles
- Cables and cords
- Small and short objects
- Moving objects
- People
- Holes and cliff edges
- Vegetation

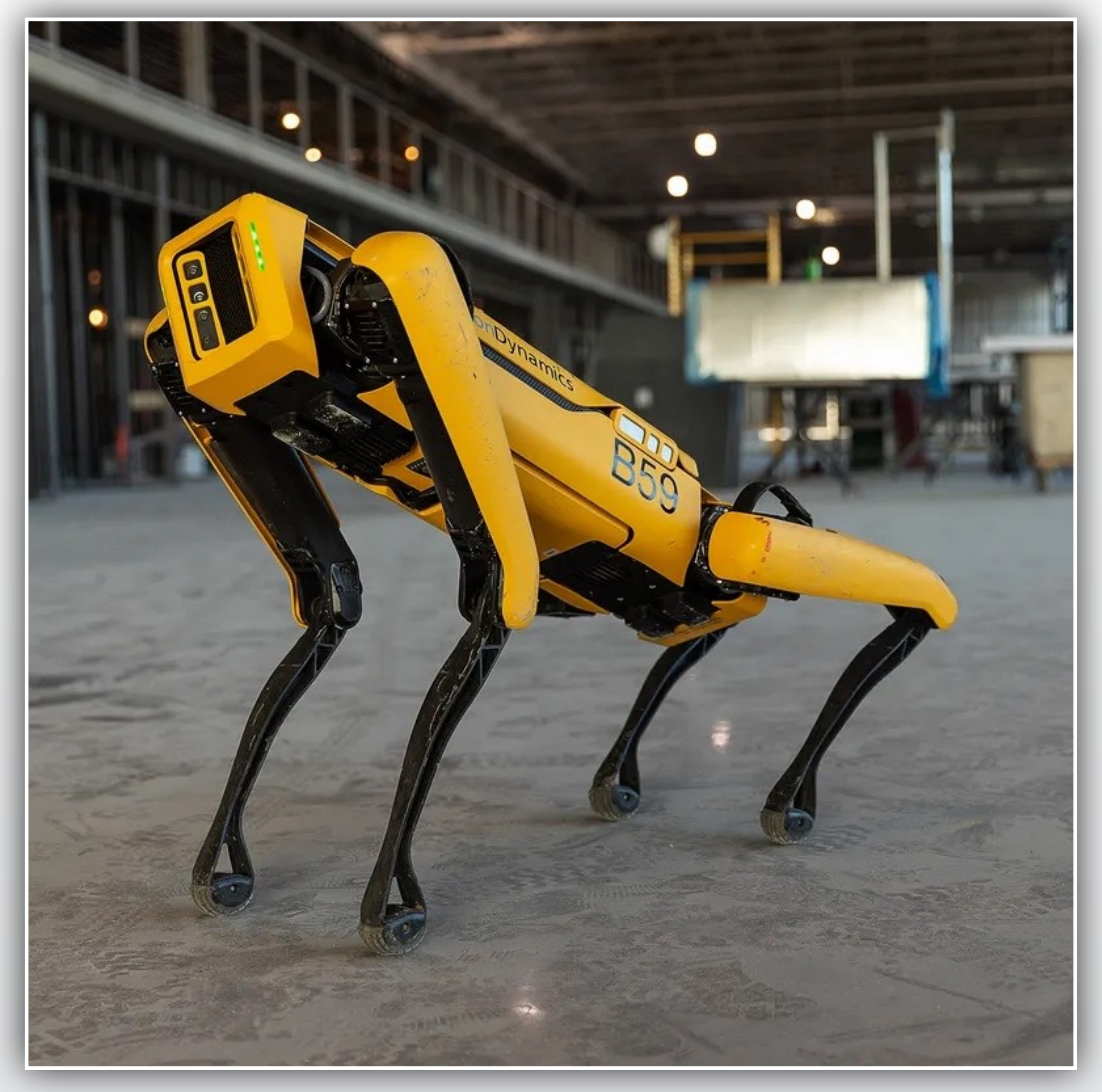


Photo: Becca Farsace

Bringing SPOT to life

THEORY OF OPERATION

Users cannot directly manipulate SPOT's individual actuators

In an attempt to increase the "user friendliness" of SPOT, the manufacturer (only) offers higher-level controls

TABLET

Option 1: Remote-controlled by human operator (complemented with some pre-programmed actions)
Option 2: Record and play back missions (with some modest autonomy) ⇝ Autowalk

WORKSTATION

Option 3: Using SPOT Python Software Development Kit (SDK)

Python code runs on external computer, which sends commands ("gRPC messages") to SPOT

No direct support for general (advanced) concepts of robot autonomy

Experts/collaborators from Sandia National Laboratories have developed a software package implementing "behavior trees" building on the original SDK and providing a greater degree of autonomy for SPOT

AUTOWALK

HOW DOES AUTOWALK WORK?

Autowalk can be used to record and (later) play back missions

Requires presence of fiducials for orientation and navigation throughout the environment

Actions can be added along the way while the map is being recorded

WHAT DOES AUTOWALK (NOT) ACCOMPLISH?

Mostly: "Go here, do this" (by default: look and take picture)

During Autowalk, SPOT can take shortcuts and avoid (previously unknown) obstacles

Limited capability to implement some logic ("If temperature at Point A too high, take picture")

Source: Boston Dynamics

SPOT "inspecting" QR codes on Princeton's VR Deck
mae.princeton.edu/about-mae/spotlight/robot-cant-remember-it-could-be-future-nuclear-arms-control

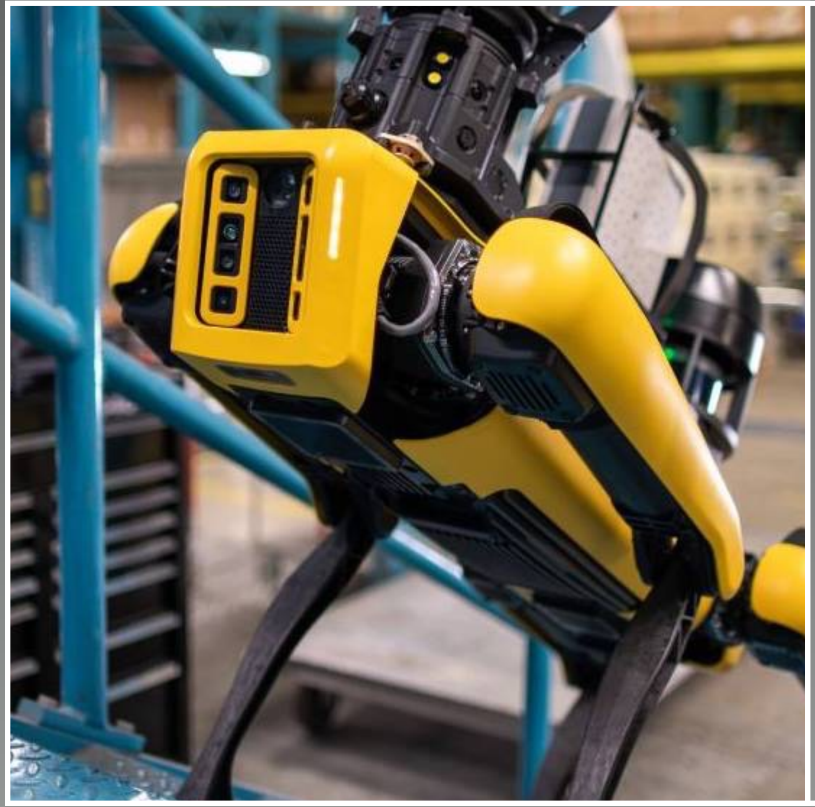
SUMMARY AND OUTLOOK

EXPLORING ROBOTIC INSPECTION APPROACHES WITH SPOT

ROBOTIC & REMOTE INSPECTIONS

Multiple rationales; in the case of fusion energy systems, it's generally assumed that inspection, maintenance, and repair will require the use of robots or other robotic devices

High levels of gamma and neutron radiation, strong magnetic fields, vacuum conditions, high temperatures, limited access, and hazardous materials



POTENTIAL AREAS FOR RESEARCH AND DEVELOPMENT

Explore plant architectures that facilitate robotic inspections for maintenance and safeguards

Consider novel sensor types for use with robotic platforms

These could include advanced optical sensors, LIDAR, gas sensors, radiation detectors, and others

Source: race.ukaea.uk (top) and Boston Dynamics (bottom)

ACKNOWLEDGEMENTS

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