

Integration of the H3D-M400 detector and Spot robot for automated area survey missions

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ABSTRACT

Area survey and search/confirmation of nuclear/radioactive sources in public areas are challenging and time-consuming tasks. When performed manually, the task also has an associated risk of exposing the operators to unknown radiation. With the help of quadruped robots like the Boston Dynamics Spot, these repeated tasks could be automated efficiently, alleviating the radiation risks to inspectors. The Spot robot comes with its software development kit (SDK) for users to write custom code in Python to control the robot. In this study, a cadmium zinc telluride (CdZnTe) detector, namely M400 from H3D Inc. has been integrated with the Spot via a Spot-CORE payload computer, allowing the robot to capture gamma spectra of background radiation and nuclear/radioactive sources present in a facility. A machine-learning model was developed to use radiation maps from the detector to predict the direction of the radiation source. Two missions have been developed, area mapping and search. In the area mapping mission, the Spot robot walks in fixed steps along a pre-recorded path and performs gamma measurements with the M400 detector. In the search mission, a custom-built algorithm navigates the Spot robot to diverge from the path toward the source location; and once in a preset distance to the source, the Spot robot will collect a gamma spectrum for a long acquisition time, e.g., 5 minutes. In both missions, operators can also use the graphic user interface to direct the robot to a specific location to collect confirmation spectra. The paper will present the details of each mission along with the test results with a ¹³³Ba radiation source in a simulated facility.

INTRODUCTION

The Office of Nuclear Smuggling Detection and Deterrence (NSDD) of the U.S. National Nuclear Security Administration (NNSA) works with partner countries to detect, disrupt, and investigate the smuggling of radiological and nuclear (R/N) materials that could be used in acts of terrorism. NSDD actively seeks to integrate recently developed technologies into its mission space. One such technology is autonomous and semi-autonomous robots. The stationary high throughput scanning missions, e.g., using Radiation Portal Monitors, can be fully automated today. In contrast, mobile area survey missions ^[1] require operators to go around a facility or public space, perform measurements manually, and identify radiation hotspots using portable handheld radiation detectors. This process is repetitive, time-consuming, and labor-intensive. In support of NSDD, BNL has explored the automation of a simple area survey mission using the Boston Dynamics SPOT robot integrated with portable radiation detectors (PRDs). The research pursued in this project may also be used in other nuclear security applications and by other federal agencies, e.g., Customs and Border Protection (CBP) in the Department of Homeland Security.

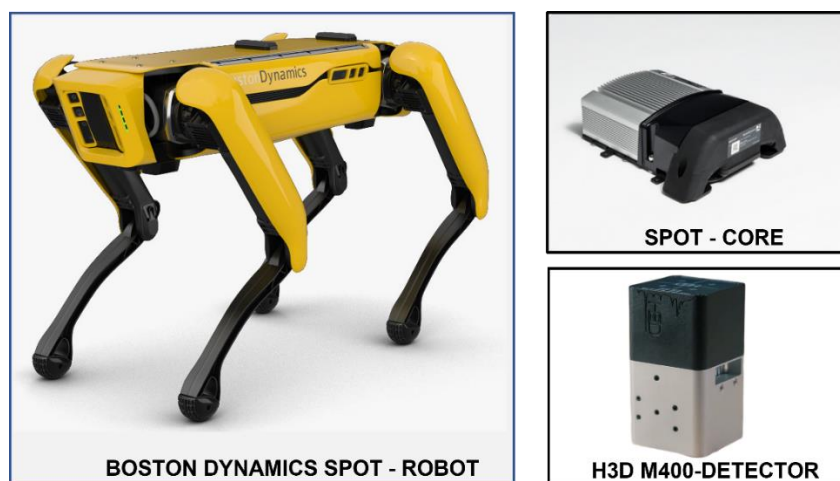


Figure 1. Boston Dynamics Spot Robot, Spot-Core, and H3D M400-Detector

In this research, a Boston Dynamics Spot robot ^[2] was used as the platform for technology demonstration. The Spot robot is an agile, easy-to-program, quadruped (four-legged) robot capable of performing routine survey tasks or missions with the assistance of custom-built software programs. Detectors can be mounted on the Spot robots and connected to its payload computer called Spot-Core ^[3] via USB or Ethernet ports. The Spot-Core comes with an Ubuntu 18.04.5 LTS operating system, which can be configured to run custom scripts written in any programming language, such as Python, C++, etc. A custom detector payload script can be developed and executed on Spot-Core, which seamlessly integrates the detector with Spot-Core allowing the Spot to communicate with and operate the payload detector via Spot-Core during its inspection routines. The Spot-Core script uses threading to perform multiple operations in parallel, like acquiring radiation data from the detector, processing the data into useful information, and transferring the processed information to another client computer connected to Spot’s network.



Figure 2. H3D M400-Detector integrated with Spot, Spot-Core system

The H3D M400 detector ^[4], a cadmium zinc telluride (CdZnTe) crystal-based gamma detector, was chosen as the radiation detector to be integrated with Spot to automate the area survey inspections. The M400 detector API not only allows the user to acquire total gamma counts and gamma spectrum but also allows the user to acquire chip-wise gamma counts. The 2x2 chip-wise gamma counts, when coupled with an ML predictive algorithm, allow for determining the direction of the radiation source relative to the detector. As shown in Figure 2, the M400 detector is integrated with Spot by connecting to the Spot-Core using an Ethernet to USB cable. The upcoming

sections discuss the M400-Spot integration structure and the programming of Spot’s area survey inspection routines in open-source Python using Spot’s software development kit (Spot-SDK) [5]. Two area survey missions have been developed – the ‘Basic Area Mapping’ mission and the ‘Advanced Area Search’ mission, each with two modes, i.e., scan and confirmation modes. The basic area mapping mission begins in the scan mode, where the Spot automatically walks along a pre-recorded route in a facility or a public space, making a finite number of stops and taking 5-second measurements using the M400 detector at each stop. At the end of the scan mode, a radiation map containing gamma counts along the traveled route is generated and fed into the confirmation mode. The confirmation mode then guides the Spot to travel to radiation hotspots and take extended five-minute measurements to generate the gamma spectra, characterizing the radioactive sources. The advanced area search mission is built on top of the basic area mapping mission. It differs from the basic mapping mission in scan mode, where the Spot uses 2x2 voxel chip-wise gamma counts and ML algorithm to predict and diverge from the pre-recorded path and move towards the radiation source. In the final demonstration, the developed Spot routines were tested by making Spot perform area survey inspection within a mock room of a facility. A 30- μC ^{133}Ba gamma source was attached to one of the walls within the area, and basic and advanced survey missions were executed. A radiation map was generated in the basic mission, highlighting the highest counts on the pre-recorded path closest to the radiation source. In the advanced mission, Spot made use of the ML prediction algorithm and M400 chip-wise counts and successfully diverged from the recorded path toward the source location in the scan mode. The source type was identified from the gamma-ray spectrum in the confirmation mode.

M400 – SPOT AREA SURVEY APPLICATION

The M400-Spot area survey application is developed in two phases based on the user requirements and functionalities provided in Table 1. The first phase is hardware interfacing, and the second phase is programming or code development. Figure 3 describes the hardware-interfacing structure and connectivity among hardware components that satisfy user requirements and functions. The Client or User Computer acts as the control center or kernel station for the entire automated M400-Spot area survey inspection system. The Spot robot with its Spot-Core and the M400 detector constitute the mobile aspect of the hardware interface representing an area survey inspector. The client computer and the Spot robot are connected via Spot’s direct Wi-Fi. The Spot-Core is mounted on the Spot robot and connected to the robot via the robot’s payload port. The Spot-Core and M400 detector are connected using a USB-A-to-USB-C cable connector.

Table 1. User Requirements and Application Functionality

Main Aspects	Functionalities
Control	<ul style="list-style-type: none"> • Start routines • Stop routines • Manual control over Spot’s locomotion
Monitor	<ul style="list-style-type: none"> • Real-time location data • Real-time camera images • Real-time obstacle grid • Real-time M400-detector gamma measurement data – counts, location
Automation	<ul style="list-style-type: none"> • Minimal user involvement • Automated navigation system

	<ul style="list-style-type: none"> Automated M400 measurements Should record and navigate to the previous measurement locations
Routines	<ul style="list-style-type: none"> Basic Area Mapping – Scan, Confirmation Advanced Area Search – Scan, Confirmation

Once the hardware connectivity is established, we begin the second phase of integration, i.e., the programming and code development to meet the user requirements and functions. The client computer and Spot-Core are two computers capable of hosting and executing code. Figure 3 describes the client-server software structure on top of the hardware structure. The GUI_kernel.py is hosted and executed on the client computer. It provides a graphic user interface for the user to start and stop Spot routines and monitor the status of the Spot robot and the M400 detector. It also contains Spot routine code, developed using the Boston Dynamics Spot-SDK package, automating the area survey inspection process by controlling the Spot robot and the M400 detector. The M400_SpotCore_Remote_Server.py is hosted and executed on Spot-Core's Ubuntu 18.04 LTS operating system. The Server code uses Python's sockets framework to communicate, operate and acquire radiation measurements from the M400 detector connected to the Spot-Core. The Server code uses Google Remote Procedure Call (grpc) framework to receive instructions and send radiation data to the GUI_Kernel.py via Spot's direct Wi-Fi network. The upcoming sub-sections briefly explain the interface with the M400 detector and Spot routine programming to automate area survey missions.

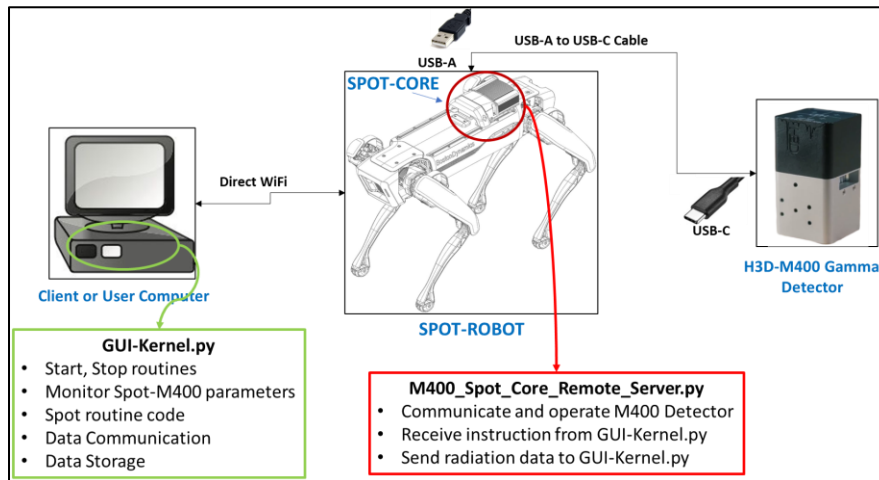


Figure 3. Hardware connectivity and software structure between the identified hardware components

M400 DETECTOR - INTERFACING

The M400 detector is interfaced and operated from Spot-Core. The Spot-Core is connected to the M400 detector using a USB-A to USB-C cable. The USB-connected detector is firmly mounted on a custom 3D-printed detector casing fixed in front of the Spot-Core on the Spot-robot, as shown in Figure 2, so the detector does not fall off when the robot is in action. The H3D vendor provides an H3D Detector API manual ^[6] that describes various methods of acquiring measurement data from the M400 detector. The manual describes three different user-accessible API formats, i.e., REST

API, N42.42-based XML API, and List-Mode API based on a FlatBuffer serialization schema. For our current purposes, we use list-mode API based on a FlatBuffer serialization schema to acquire and process measurement data from the M400 detector. The list-mode API provides a steady data stream of list-mode gamma-ray event information, time sync, and GPS data (optional). The schema file in Appendix B contains the FlatBuffer format which the data stream is serialized and hosted using a TCP/IP connection on port 11503 of the M400 detector’s IP address (192.168.6.10). A client can connect to port 11503 of 192.168.6.10 using sockets and start streaming the binary data through the connection. The first byte of the data packet contains information on the packet size of the payload data the detector will be streaming to the client. The data packet contains total gamma interactions and gamma event information, i.e., interaction energy (Kev), interaction location (chip_no, x, y, z), that are accumulated during the time elapsed between the previous request and the present request. For example, to perform a 5-second measurement, the client first connects to the M400 detector port and streams accumulated data resetting the existing counts. Then the client waits for 5 seconds, and another streaming operation is performed to get the 5-second accumulated gamma events from the detector. The detector will return the counts accumulated between the first and second requests, corresponding to a 5-second measurement. The streamed data buffer must be parsed into gamma events and interactions using the flat buffer schema of the H3D API manual's Appendix B. Appendix C of the same manual provides a Python example for operating the M400 detector in list mode. Thus, a custom Python function is developed based on the provided example in Appendix C, which is embedded within the Python script `Spot_Core_D3S_Server_Code.py` and executed on Spot-Core. The code has an additional grpc server framework that actively listens for any measurement requests from the client computer, performs M400 measurements, and sends the data back to the client computer.

SPOT ROBOT – PROGRAMMING

The Boston Dynamics Spot SDK ^[5] is a collection of open-source Python modules which can be installed and imported like any other Python module. It contains classes, client services, and functions necessary to develop Spot routines tailored to perform specific tasks. Table 2 contains all Spot SDK services and functionalities needed to build Spot routines for area survey missions.

Table 2. Required Spot SDK services and functionalities to perform secondary inspection routines

S.No	Services	Functionality
01.	Robot State Client	Acquire state parameters like robot location, power on/off, etc.
02.	Robot Image Client	Used to acquire RGB and depth images from robot cameras
03.	Robot Estop Client	Used to set up robot emergency stop and release buttons
04.	Robot Lease Client	Necessary to control robot motors and locomotion
05.	Robot Power Client	Allows the user to turn on or off robot motors
06.	Robot Command Client	Contains commands to navigate the robot in various reference frames
07.	Robot Local Grid Client	Contains commands to acquire information on terrain, obstacles, heights, etc.
08.	Robot GraphNav Client	Contains commands to pre-record, load, and navigate the robot along a fixed path within a facility
09.	Robot Remote Mission Client	Contains commands to setup and run remote missions like performing M400 measurements

The M400-Spot area survey missions (Basic Area Mapping Mission, Advanced Area Search Mission) and their sub-routines (scan mode, confirmation mode) are coded in `GUI_Kernel.py` and executed on the client computer. The general structure or algorithms corresponding to each mission

and their sub-routines are discussed in Table 3. The algorithms described here are designed to automate the area survey missions completely. They primarily rely on Spot’s GraphNav navigation system for recording and transverseing the inspection route, the local obstacle grid system to identify and avoiding obstacles, and custom-developed ML direction prediction algorithm to predict the source direction based on M400 detector’s 2x2 chip-wise gamma counts. Figure 4 visually describes each of the mentioned systems.

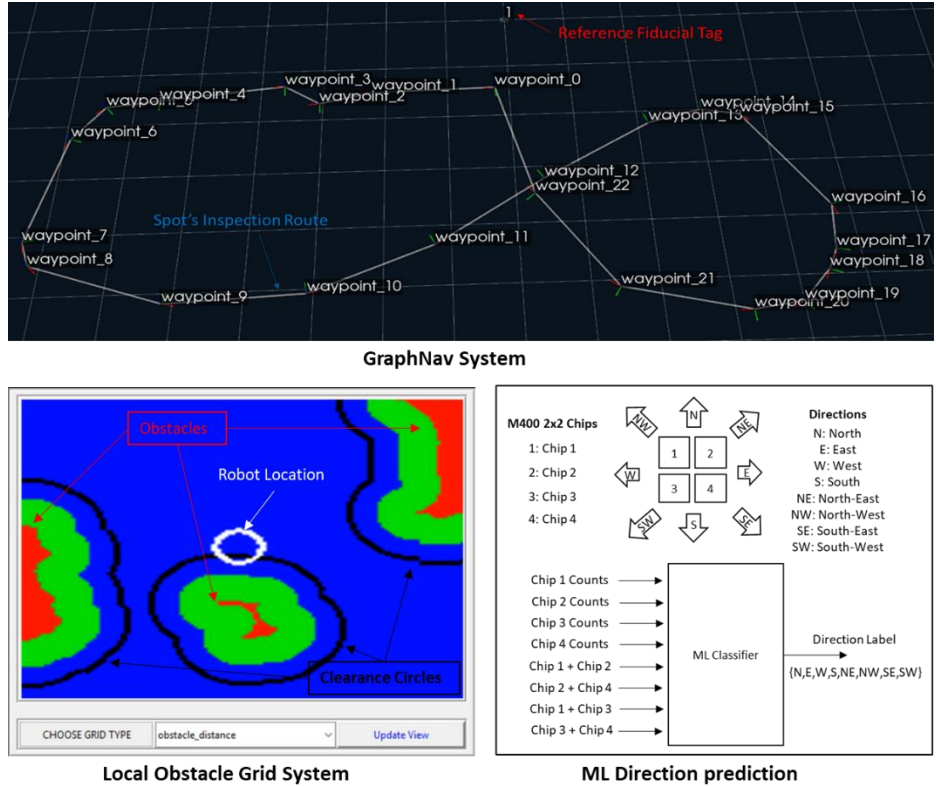


Figure 4. Primary components or features required for executing the Table 3 algorithms.

Table 3. General structure or Algorithms corresponding to Basic Mapping and Advanced Search Missions

M400-Spot Mission	Algorithm or General Structure
<p>Basic Area Mapping Mission</p>	<p>Scan Mode</p> <ol style="list-style-type: none"> 1. Upload the map of the inspection path within the facility to robot’s GraphNav System 2. Initiate the robot’s location on the map based on a reference fiducial. 3. Perform 5-second background gamma measurements using the M400 detector. 4. Walk for 3 seconds towards the next waypoint and perform a 5-second M400 measurements. 5. Acquire, store, and update Gamma measurement data and measurement location on the GUI system. 6. Repeat steps 4 and 5 until the robot is back to its starting location. 7. Generate a Gamma radiation map to identify potential radioactive source locations and initiate. confirmation mode for source identification. <p>Confirmation Mode</p> <ol style="list-style-type: none"> 1. Acquire the radiation map from the scan mode. 2. Navigate to a location with high radiation and perform extended five-minute M400 measurements. 3. Generate and save the Gamma spectrum at the source location. 4. Repeat steps 2 and 3 for any other high-radiation locations displayed on the radiation map. 5. Finally, return to starting location, sit, and safely shut down the robot

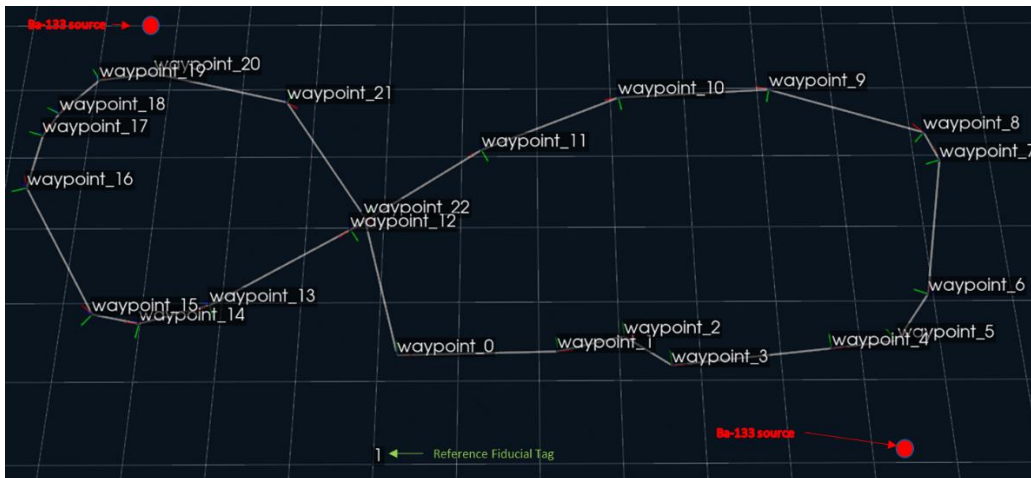
Advanced Area Search Mission	<p>The Advanced Search mission is built upon the Basic Area Mapping mission and follows similar steps for both scan and confirmation modes. A source-seeking algorithm is executed between steps 5 and 6 of scan mode, which allows the robot to divert from the inspection path toward the radiation source using the M400 chip-wise gamma counts and ML direction prediction model.</p> <p>Source Seek Mode: Check if measured gamma counts > 1.5*Background counts:</p> <p>IF YES:</p> <ol style="list-style-type: none"> a. Use the ML algorithm to predict the direction of the radiation source relative to the robot. b. Navigate towards the source in steps of 0.5 meters using the command client's relative move function. c. Perform M400 measurements, save and update data on GUI d. Repeat steps a, b, and c until robot is close enough to the source or cannot move any closer due to obstacle detection. e. Return to the inspection path and continue to step 6 of scan mode <p>ELSE:</p> <ol style="list-style-type: none"> a. Continue to step 6 of scan mode
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Ba-133 TEST RUN RESULTS

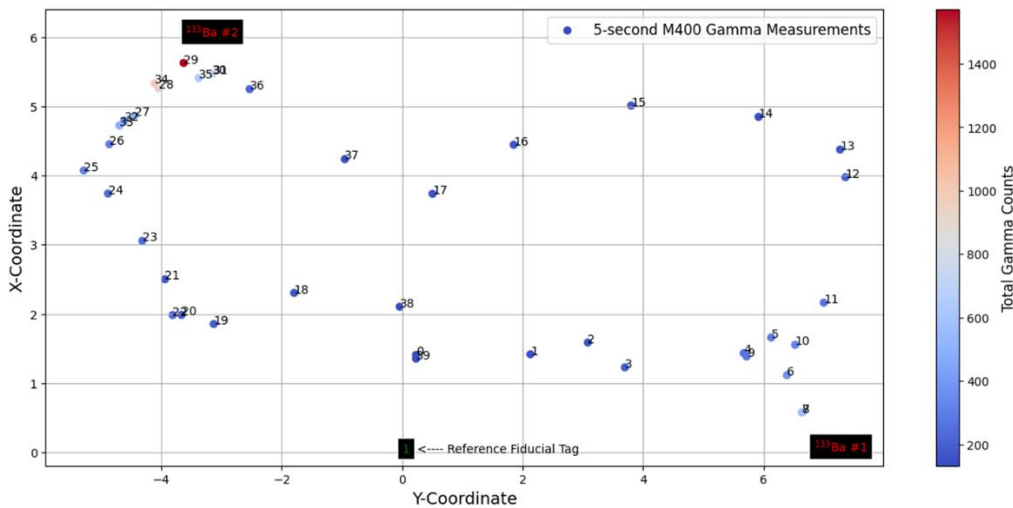
The developed platform was tested for technology demonstration by area surveying a room for radiation hotspots. The M400_Spot_Core_Remote_Server.py is executed on Spot-Core, hosting a server that actively waits for commands from GUI_Kernel.py executed on the client's laptop computer. Operators monitor the system using the graphic user interface of GUI_Kernel.py on the client computer. The inspection route within the room is recorded using the recording_command_line.py example of Spot-sdk. The recorded map, shown in Figure 5, is uploaded onto the robot, and the robot's location is initialized using reference fiducial tag 1. The basic area mapping and advanced area search missions are executed with a 30- μC ^{133}Ba sealed source attached along various locations on side walls within the room. Since the advanced area search mission includes basic area mapping, we only present the results for scan and confirmation modes of the advanced search mission in the following sub-sections.

SCAN MODE RESULTS

Upon initiating the advanced mission, the scan mode was activated, and the robot moved along the inspection route, performing 5-second gamma measurements at each stop along the route. When the total counts at measurement location #5 is measured to be greater than the threshold counts (1.5*background). In that case, the robot deviated from the path and converged toward the radiation hotspot in multiple steps, i.e., #6, #7, and #8. Upon converging onto the radiation source at #8 and can no longer get closer to the source, robot returned to the original route and continued along the inspection route. To simulate a second source, the ^{133}Ba source at waypoint #4 is moved and attached to the wall near waypoint #20, hoping that the robot will detect and converge to the new source location while scanning along the inspection path. This source-seeking behavior is indeed observed and is shown in Figure 5, where the final gamma radiation map depicts the robot closing onto the radiation sources each time it detects them. This can be further confirmed by the increase in total counts, seen in the figure by changes in the color towards red as the robot approaches the radiation sources. The scan mode ends when the robot returns to starting location. All the data and plots corresponding to the scan mode are automatically stored on the client's computer, and the data is displayed on the GUI system. The end of scan mode automatically prompts the user to initiate the confirmation run to identify radiation sources.



Inspection Scenario



Gamma Radiation Map

Figure 5. Inspection Scenario and advanced mission’s scan mode Gamma radiation map

CONFIRMATION MODE RESULTS

The confirmation mode is initiated at the end of the scan mode inspection run. The highest gamma count location from the radiation map, i.e., #29 or (5.67, -3.64), is set as the target location. The Spot navigates to the location (5.67, -3.64) and performs a 5-minute M400 measurement generating a gamma spectrum. Figure 6 shows the gamma spectrum of the Ba-133 source with characteristic 356, 303, and 276 keV gamma peaks. Once the robot finishes the assigned measurements, it automatically returns to the starting location and waits for further instructions from the operator. The confirmation mode results are automatically processed, saved onto the client computer, and displayed on the GUI system.

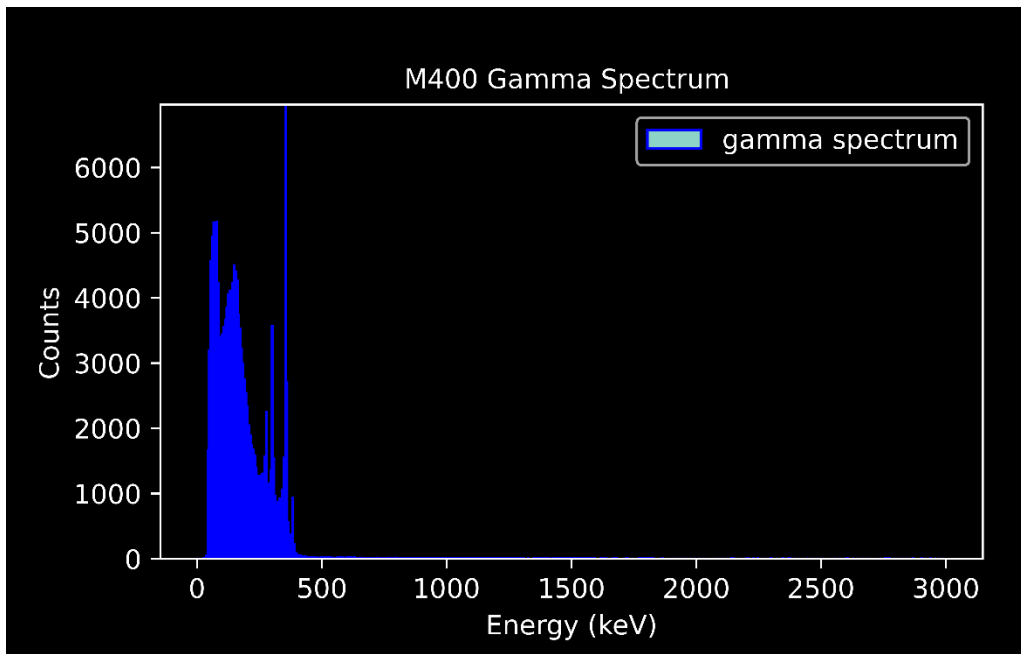


Figure 6. Confirmation Mode – ^{133}Ba source gamma spectrum collected at the location (5.67, -3.64) of the radiation map shown in Figure 5.

CONCLUSIONS

An automated area survey inspection system has been developed based on the H3D M400 detector and the Boston Dynamics Spot robot. The system successfully conducted basic area mapping and advanced area search missions within a facility with a sealed ^{133}Ba source. The demonstration showed the potential of this novel platform in nuclear material security applications. Future work may involve further improving the software to address the challenges encountered in a more complex operational environment and developing custom routines to automate other tasks in nuclear material accountancy and homeland security.

ACKNOWLEDGEMENTS

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