

RADIATION IMAGING FOR WASTE MANAGEMENT AND DECOMMISSIONING

K. Stoev, P. Rochefort, M. Banks and N. Simpson

Canadian Nuclear Laboratories, Chalk River, Ontario, Canada

krassimir.stoev@cnl.ca, paul.rochefort@cnl.ca, mike.banks@cnl.ca, nicholas.simpson@cnl.ca

Abstract

The need for equipment capable of remote localization and quantification of radiation sources (point sources, hot spots, radiation hazards, contamination, etc.) has already been reported. For waste management and decommissioning (WM&D) purposes, radiation hazards must be identified before removal. Development of a remotely-operated radiation imaging device, which can be incorporated into robotic systems, will enable operators to locate irradiating sources in “near real-time”. Possible uses of such a system include: (i) directional localization of radioactive sources and contamination; (ii) 3-D evaluation of dose-rates, source activity, and isotope identification; (iii) continuous monitoring of radiation fields; and (iv) detection of nuclear and radiological threats. This paper will review current state-of-the-art radiation imaging technology. Recent work at CNL on developing radiation imaging devices is discussed; especially the development of radiation imaging devices to be incorporated in remotely operated robotic systems. The operational parameters of the developed prototypes are represented.

1. Introduction

There is a well-identified need for equipment to localize and quantify radioactive sources. This is especially true for certain industries:

- Waste management, where hot spots, radiation hazards, and contaminations must be identified before processing.
- Decommissioning and decontamination activities, where any radiation hazard has to be established before work can begin.
- The nuclear industry, where radiation sources have to be localized and measured during routine operation or accidents.
- National security, including military/defence and nuclear non-proliferation organizations, where nuclear and radiological threats have to be identified.

Development of a remotely operated radiation imaging device, which can be incorporated into robotic systems, will enable the location of irradiating sources in “near real-time”. Possible uses of such a system will be:

- Directional localization of radioactive sources.
- Three-dimensional (3D) evaluation of dose-rates and mapping of radiation fields.
- 3D identification of emitting isotopes and evaluation of source activity.
- Continuous monitoring of radiation fields.

CNL is in the process of developing robotic concepts for high radiation environments. Current work is concentrated in the following areas:

- Review available technologies for radiation imaging.
- Compare advantages and disadvantages of different technologies for radiation imaging, and study their limitations and characteristics.
- Identify the needs and requirements to be considered.
- Select the parameters which need to be specified when choosing radiation imaging devices.
- Select the most appropriate radiation imaging technologies for robotic applications.
- Perform preliminary experiments to demonstrate applicability of radiation imaging techniques.

2. Types of radiation imaging devices

For the purposes of this paper, a gamma-imaging system is defined as a system that can generate information about source(s) location and direction. This should be information that can be superimposed onto a regular digital picture taken with a conventional camera.

There are four important types of nuclear radiation: alpha particles; beta particles; gamma photons; and neutrons. Alpha and beta radiation have limited penetration power, and they are usually detected with contact or near-contact methods. For WM&D purposes, imaging of gamma sources is of great importance, because most of the dose to personnel comes from gamma sources. Therefore, only gamma imaging devices will therefore be considered in this paper.

Gamma-radiation detectors can be classified as:

- Energy-Dispersive: Energy of each detected gamma-photon is measured.
- Dose-rate Measuring: Total energy per unit time, deposited into the detector volume, is measured.

Gamma-radiation detectors can also be separated in two groups according to their configuration: (i) single-element detectors, and (ii) multi-pixel detectors (i.e., position sensitive detectors). Gamma-imaging systems that employ the following types of detectors will be considered:

- Dose-rate Measuring, single-element detectors.
- Energy-Dispersive, single-element detectors.
- Dose-rate Measuring, multi-pixel detectors.
- Energy-Dispersive, multi-pixel detectors.

After a literature review, a list of the available gamma-imaging technologies was prepared:

- **Systems Based on Grazing Incidence Optics**[1]. These systems use total reflection to form an image and usually are used in the x-ray region below 20 keV. These systems employ dose-rate based, position-sensitive detectors.
- **Systems Based on Scanning Collimated Detector**. These systems can use either dose-rate or energy-dispersive single element detectors. Due to limited field of view, a pan-tilt system for scanning is required.

- **Systems Based on Rotating Modulating Collimator (RMC)**[2]. These systems are based on temporally-modulated single non-position-sensitive dose-rate detector. Due to limited field of view, a pan-tilt system for scanning is required.
- **Inverse Collimation Systems**[3]. These systems are based on a “shielding-pencil” configuration, and can use either dose-rate or energy-dispersive detectors. A pan-tilt system for scanning is required.
- **Structured Multi-Detector Systems**[4]. These systems are based on the use of several detectors and an assembly of shielding walls/rods around them. For such systems, the response of each detector will depend on the relative position of the source, and will be different for each detector. This would allow for reconstruction of the direction and intensity of the source based on the information from all detectors. These systems can use either dose-rate or energy-dispersive detectors. A pan-tilt system for scanning may be required.
- **Pinhole Gamma Camera**[5]. These systems can use either dose-rate or energy-dispersive detectors. A pinhole gamma camera is the simplest gamma-imaging device based on a position-sensitive detector. It has two main components: (i) an opaque shield with a hole in it, and (ii) a position-sensitive detector.
- **Multi-Hole Collimator Systems**[6]. These systems are usually used in medical radiation imaging, to reduce scattering effects and improve image quality. They use a position-sensitive pixilated detector, with a separate collimator (hole) for each pixel.
- **Coded Aperture Gamma-Cameras**[5, 7]. These systems are very similar to pinhole gamma cameras, but have a collimator with multiple holes and a position sensitive detector. They differ from multi-hole collimator systems in that there is no separate collimator hole for each pixel.
- **Compton Gamma Camera**[8]. These systems are based on the Compton Scattering effect. They are composed of two planar (i.e., flat) pixel-based position-sensitive energy-dispersive detectors.

Comparison of the different gamma imaging techniques is presented in Table 1. After reviewing the capabilities of the gamma imaging methods, it can be concluded that for land-based robotic applications, the preferred methods are: **(i) Pinhole Cameras; (ii) Coded Aperture Cameras; and (iii) Structured Multi-Detector Systems.**

All other methods are not easily adaptable for use on mobile robotic platforms because of size, weight, or do not meet design requirements. A summary of the parameters of several commercially available gamma imaging devices (both systems and modules) is presented in Table 2. This information was obtained from public domain websites. Several imaging subsystems (CrystalCam, Minicam, SPECT-DM, NV-100, Medipix2) that can be used for in-house gamma imaging system construction are also included in this table. All of the cited complete gamma camera systems (CARTOGAM (discontinued), GamPix, LT31, Polaris, HSL-500, RadCam) cost in excess of \$100,000. Except for GamPix (also advertised as iPIX) all other gamma cameras are large and heavy, and are not designed to be used in a mobile robotic platform. It is worth noting that a structured multi-detector system known as RadCompass (offered by BTI, <http://bubbletech.ca>) is not included in Table 2, but this system is very suitable for robotic application, because it is essentially a directional gamma detector.

Table 1. Summary of parameters of gamma imaging methods.

System	Detector Type	Energy Range	Angular Resolution	Energy Resolution	Field of View	Imaging Speed	Efficiency	Size	Weight	Usability for WM&D Robots
Grazing incidence optics	Position-sensitive, dose-rate	< 20 keV	Very good	-	Very small, scan-motion required	Good	Low	Large	Medium	No
Scanning collimated detector	Single element, dose-rate or energy-dispersive	Full	Acceptable	Good	Very small, scan-motion required	Very slow	Low	Small	Medium	Limited use
Rotating modulating collimator	Single element, dose-rate	Limited	Good	-	Small, scan-motion required	Acceptable	Medium	Large	Medium	No
Inverse collimation system	Single element, dose-rate or energy-dispersive	Full	Acceptable	Good	Scan-motion required	Very slow	Good	Small	Small	Limited use
Structured multi-detector system	Multi element, dose-rate or energy-dispersive	Full	Acceptable	Good	Wide scan-motion may be required	Fast	Good	Small	Medium	Yes
Pinhole gamma camera	Position-sensitive, dose-rate or energy-dispersive	Full	Acceptable	Good	Medium	Acceptable	Low	Small	Medium	Yes
Multi-hole collimator imager	Position-sensitive, dose-rate or energy-dispersive	< 200 keV	Acceptable	Good	Relatively small	Acceptable	Medium	Small	Small	Limited use
Coded aperture gamma camera	Position-sensitive, dose-rate or energy-dispersive	Full	Acceptable	Good	Medium	Fast	Medium	Small	Medium	Yes
Compton gamma camera	Position-sensitive, energy-dispersive	0.3 to 3 MeV	Fair	Good	Medium	Acceptable	Good	Large	Medium	Limited use

Table 2. Summary of parameters of commercial gamma imaging devices¹ (systems and modules).

Company	Model	Optics	Detector	Pixels	Max. Energy [keV]	Energy Resolution	Sensitivity for ¹³⁷ Cs	Maximum Dose-Rate	FOV	Angular Resolution	Size [mm]	Weight [kg]
Canberra	CARTOGAM	Pinhole	CsI(Tl) or BGO	Video	1500		300 nSv/h for 30 min	10 Sv/h	43°x33°	2.5°	80x120x450	40
Canberra	GamPix	Coded Mask	CdTe (14x14x1mm)	256x256	1250		2.5 µSv/h for 60 sec		30°	3°	150x60x50	0.3 + shielding
Crystal Photonics	CrystalCam sub-system	None	CdZnTe (40x40x5mm)	16x16	660	7% @140keV					60x60x160	0.8 + shielding
EuroRad	Minicam	Multi-Hole	CdTe (40x40x5mm)	16x16	200	7% @140keV					φ95x150	1.5
Kromex	SPECT-DM sub-system	None	CdZnTe (44x44x5mm)	22x22	3000		<4x40,000 cps				216x137x73	
EXELIS / NII	LT31	Coded Mask	Scintillator	Video 594x446	1500		< 1 µR accumulated		50°	2.6°	262x264x544	21
H3D	Polaris	Compton	CdZnTe (pixel=2x2x1.5m)	2 x 3 x 3	1500	0.9% at 662 keV						5
IMI	NV-100 sub-system	Multi-Hole	NaI (5x5 cm), pixel	29x29		12% at 140 keV	10 cps/µCi					1.5
Innovative Physics	HSL-500	Coded Mask	CsI(Tl)	Video			0.5 µSv/h for 3 min	50 µSv/h	60°	10°	261x204x337	20
Kromex	RadViz	Scanning			2000	3% at 662 keV	2h per scan	1 Sv/hr				15
RMD	RadCam	Coded mask	CsI(Na)		1500		2 min for 3.7x10 ⁸ Bq		35°			
XIE	Medipix2sub-system	None	CdTe (14x14x2mm)	128x128	1250							

¹All data presented in the table is from public sources.

3. CNL robotic concept

CNL is constructing a prototype robot that can operate in a radiation environment. The main function of the robot will be to inspect and manipulate sites where personnel-entry is not advisable. The robot will be a remotely operated mobile platform, with the following add-on components (modules) available for performing required tasks:

- **Manipulator Arm:** For moving and collecting objects, preferably with a separate camera mounted in the mechanical “hand” for close-up video of manipulated objects.
- **Navigational (Panoramic) Cameras:** Several fixed cameras used in moving the robot and observing the surroundings.
- **Visual Inspection Camera:** A pan/tilt high-quality zoom camera for visual inspection, preferably with integrated lighting.
- **Directional and Wide-Angle Illumination:** Lights, attached to both the Manipulator Arm and the Visual inspection camera.
- **Three Dimensional Mapping:** A stereo camera, or similar device, used to create a 3D model of the inspected site.
- **Infrared Radiometric (Thermal) Camera:** Preferably on a separate pan/tilt stage.
- **Multi-spectral (hyper-spectral) camera:** For identification of hazardous substances (e.g., gases).
- **Global Positioning System:** GPS, or other form of position recording system.
- **Temperature and Humidity Measurement device.**
- **Low Dose-Rate Detector:** Fixed detector, for evaluation of the dose-rate at the position of the robot. These will be high-sensitivity detectors that can detect significantly distant radiation-threats.
- **High Dose-Rate Detector:** Fixed detector, for evaluation of the dose-rate at the position of the robot in high radiation fields, where the low dose-rate detector could saturate.
- **Directional Dose-Rate Detector:** A set of shielded fixed detectors. This assembly can also be used as a low dose-rate detector, but in addition to measuring the dose-rate at the position of the robot, it also will be able to provide information about the direction from which the radiation originates.
- **Gamma Imaging:** A system consisting of several co-aligned modules:
 - Visual Supervisory Camera
 - Gamma Camera
 - Range Finder (laser- or ultrasound-based)
 - Collimated Gamma Spectrometer
 - Laser Pointer or Structured Light Source (optional)
 - Pan/Tilt Gamma Imaging Mount (optional).

Permanent mounting of all modules on the moveable robotic platform may prove to be impractical. It is therefore important to design the robotic system with the capability to add/remove different measuring or manipulating modules.

The expected order-of-use for the radiation devices of the robot is as follows: The low dose-rate detector will be used for monitoring the field at the position of the robot. If an increase in the dose-rate is observed, the directional dose-rate detector (possibly the same module as the low dose-rate detector) will be used to determine the direction of the radiation source. The robot will be moved (rotated) so the co-aligned gamma imaging system is pointing toward the radiation

source. Images with the co-aligned supervisory (visual) and gamma cameras will be generated. The supervisory camera will have a slightly larger field of view than the gamma camera, so the images from both cameras can be fused, and the source(s) of radiation can be identified. After the source is identified, the robot can be moved so the source is in the centre-of-view of the supervisory camera, which will allow the range finder to determine the distance to the source, and the collimated gamma spectrometer to identify the isotopic content of the source. Based on the measured dose-rate information, distance to the source, and isotopes present at the source, the activity of the source can be calculated.

4. Requirements for specifying gamma imaging devices for robotic applications

After analysing the gamma imaging device user-requirements, and the restrictions imposed by the robotic system, the following specifications and design parameters were formulated for the robotic gamma imaging system:

- **Field of View (FOV):** The gamma camera shall have FOV in the range from 15 degrees to 50 degrees.
- **Pan/Tilt:** The co-aligned gamma imaging system shall have pan/tilt capabilities, or equivalent scanning capabilities.
- **Angular/spatial resolution:** Angular resolution of the camera shall be in the range from 1 degree to 5 degrees.
- **Source Ranging:** A non-invasive range-measuring instrument and a laser pointer (or laser pattern projector) may be included on the robotic system.
- **Sensitivity:** The camera shall have a sensitivity that allows it to detect local fields having dose-rate as low as 10 $\mu\text{Sv/h}$ (1 mR/hr) for photon energies in the range of 30 keV to 3 MeV.
- **Dynamic range:** The camera shall be capable of detecting sources that generate radiation fields at the camera position that vary by up to a factor of 20^2 .
- **Dose-rate range:** The camera shall remain functional in a radiation field of up to 1 Sv/h (100 R/h).
- **Image acquisition time:** The system shall be capable of producing a gamma-image in 30 minutes or less.
- **Size:** The camera shall have a footprint smaller than 110 mm x 150 mm.
- **Weight:** The gamma camera total shielded mass shall be less than 20 kg.
- **Working Environment:** The camera shall be capable of operating from -40 to +40 °C, indoors and outdoors. Cooling or heating of the camera shall be allowed.
- **Data:** The gamma imaging system shall be capable of producing a gamma-field data file that can be overlaid onto a visible image³.
- **Cost:** It is expected that the retail cost of the gamma imaging device will be lower than those presently available, with a target cost of less than \$50,000 CAD.

² This is based on 8-bit imaging or 255 grey-tones.

³ This will allow determination of the source-direction, potential identification of the source, and location of the source using triangulation from two camera positions.

5. CNL prototype gamma imaging device

Based on the specifications for the gamma imaging system, a prototype fully-shielded pinhole gamma camera was designed, fabricated and tested. A diagram and photograph of the gamma camera are shown in Figure 1.

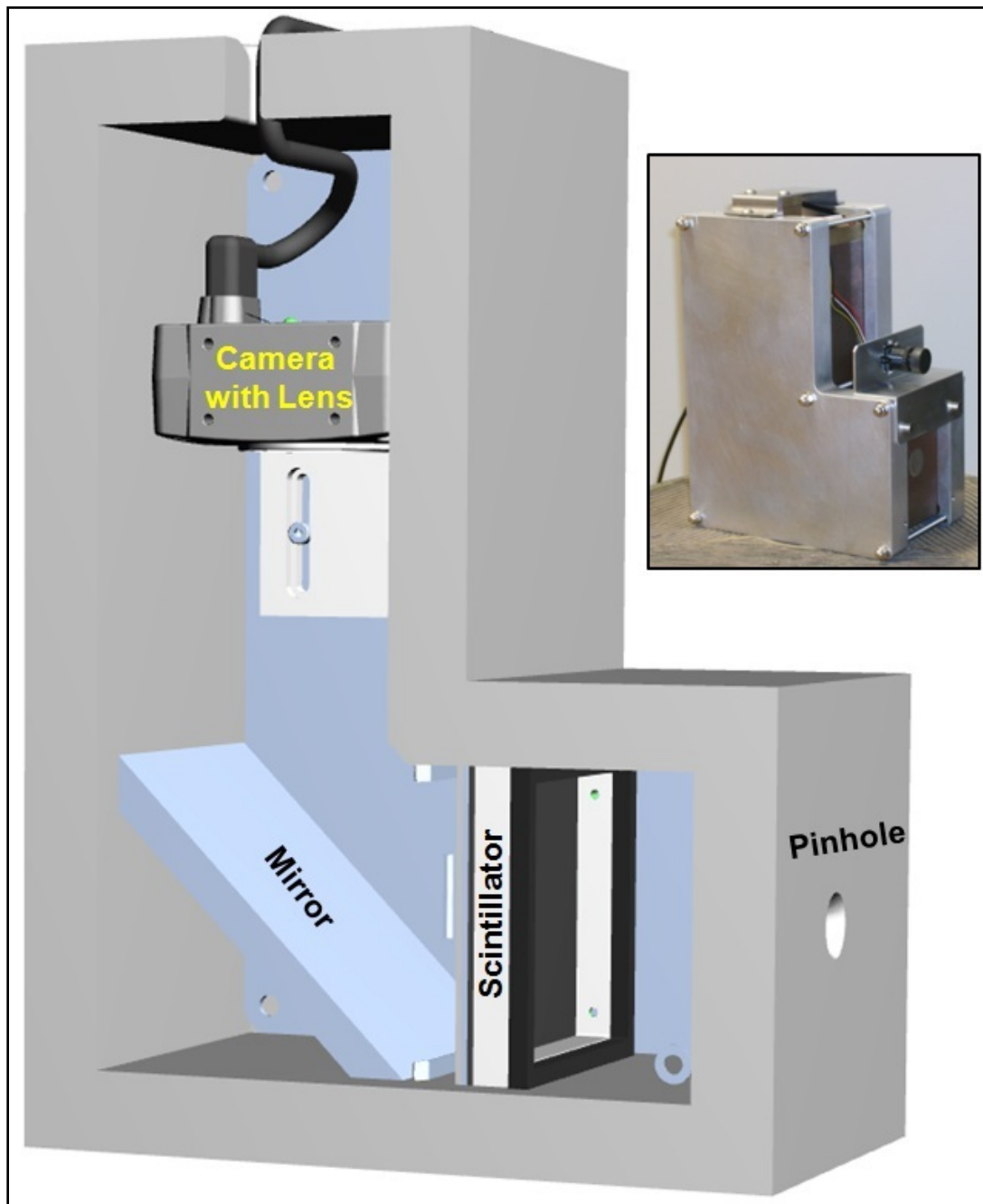


Figure 1 Prototype gamma camera.

The camera was produced from 13mm thick tungsten-alloy sheet, which provides sufficient shielding to allow operation of the camera in radiation fields from 10 $\mu\text{Sv/h}$ to 1 Sv/h (1 mR/h to 100 R/h). Independent tests were performed on commercially available x-ray intensifying screens and scintillators, and the best combination of an x-ray intensifying screen and a scintillator was selected, which allowed for simultaneous detection of x-rays with energy as low as 30 keV and gamma rays with energy up to 3 MeV. Seven high-sensitivity low-light cameras were tested to determine their applicability for use in the prototype gamma camera. The DH15 (Tucsen Discovery) camera had the best low-light performance (high sensitivity, low noise, long integration time), but due to its size it was not integrated into the prototype gamma camera. Ultimately, a small board-level low-light camera (CC1546), based on a 1/3" Sony EXView high sensitivity low-noise CCD sensor, was selected. This camera has exposure times from 1/1000 sec to 4 sec with digital slow shutter mode set to integration of 256 frames last displayed (FLD).

Initial testing of the x-ray camera was done inside an x-ray cabinet. Low-density scattering objects were placed in front of a lead (Pb) sheet and were irradiated with x-rays. The backscattering of the objects was recorded with the gamma camera. Essentially the same setup is used for back-scattering radiography. Figure 2 summarizes the single frame gamma-camera response at different dose-rates with the CC1546 camera was set to an exposure time equal to 256 FLD, or 4 sec. As can be seen, dose-rate levels as low as 0.1 mSv/h (10 mR/h) can be observed in real time, using single frames and an exposure time of 4 sec. For a single frame image with exposure time of 4 sec, the saturation point is approximately 15 mSv/h (1500 mR/h), which is within the expected range for 8-bit (or 255 grey-scale images). For the fastest CC1546 exposure time (1/1000 sec), the approximate maximum dose-rate that will result in saturation of the image will be 60 Sv/h (6 kR/h), based on a linear interpolation.

The next test was done with a micro-focus x-ray tube, again in reflection geometry. In this case, a different image processing technique was applied. A video was recorded for both the source (x-rays were on) and background (x-rays were off). All frames of the video for the background radiation were averaged. Afterwards, the averaged background was subtracted from each frame of the source video, and the net frames were summed. The results are shown in Figure 3 for simulated sources (scattering objects) that generate radiation fields, at the gamma-camera pinhole position, of 1.7 mSv/h (170 mR/h) (image integration time of 1 min) and 10 $\mu\text{Sv/h}$ (1 mR/h) (image integration time of 5 min). As can be seen in the right picture presented in Figure 3, the image of the scattering object is slightly brighter than the surrounding areas, so this can be considered the detection limit for the presented gamma camera. Similar results (not shown) were obtained with a gamma source producing 7 $\mu\text{Sv/h}$ (0.7 mR/h) at the pinhole position, but in this case the image integration time was 30 minutes.

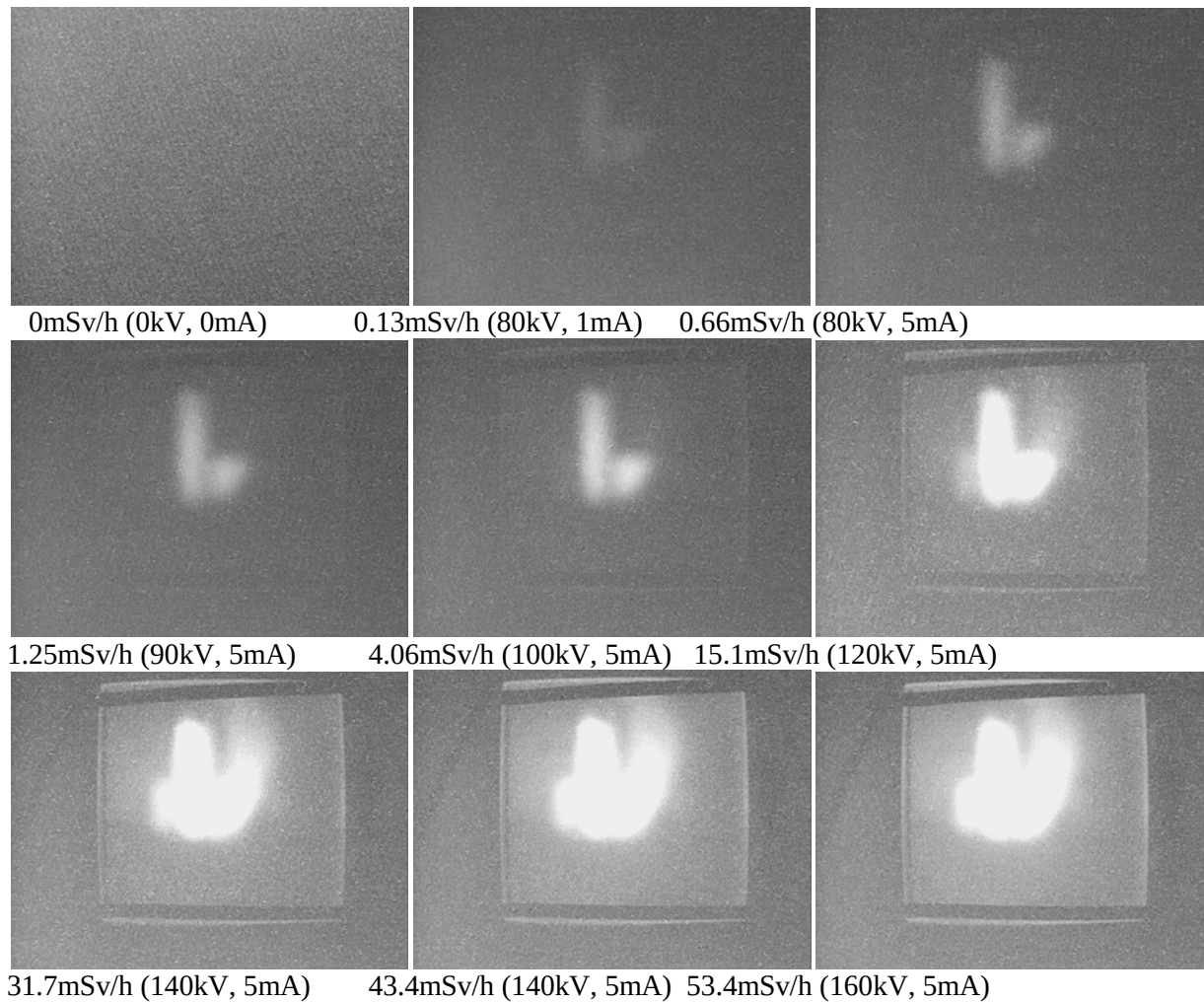


Figure 2 Response of the gamma-camera to different dose-rates.

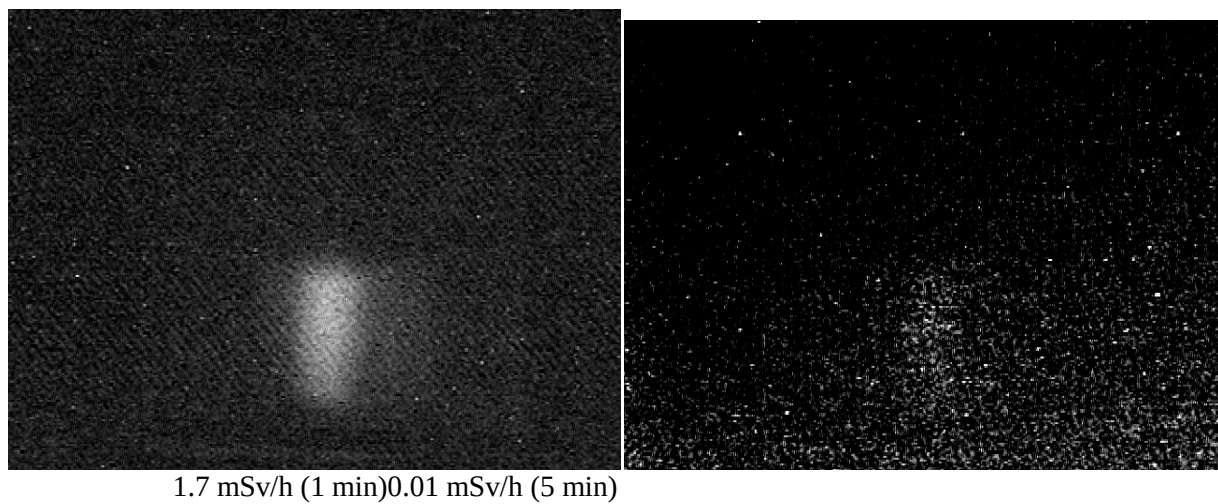


Figure 3 Gamma-images with subtraction of dark image.

6. Conclusion

CNL is in the process of developing radiation imaging devices specifically designed for incorporation in remotely operated robotic systems. Such systems will be useful for the work done by the Waste Management & Decommissioning departments, emergency and security workers, and military personnel. A literature review of gamma imaging techniques has been carried-out, and pinhole cameras, coded aperture cameras, and structured multi-detector systems have been selected as the preferred methods for gamma-imaging for robotic applications. After reviewing waste management/decommissioning requirements, a CNL robotic concept has been finalized, and is presented in this paper.

The main tasks of the robotic system will be inspection and manipulation of objects in sites where it is not advisable to send people. The robot will be based on a remotely operated mobile platform, and will have replaceable components/modules, which will be selected and installed for each specific task. After analysing the needs of the users of the gamma imaging device, and the restrictions imposed upon the gamma imaging system by the robotic system, requirements have been specified. Based on these specifications, a prototype fully-shielded pinhole gamma camera has been designed, fabricated and tested. Experiments have confirmed that the camera can be used for radiation imaging of radiation fields as low as $10 \mu\text{Sv/h}$ (1 mR/h).

7. References

- [1] C.J. Burrows, R. Burg, and R. Giacconi, "Optimal Grazing Incidence Optics and its Application to Wide-Field X-Ray Imaging", *Astrophysical Journal, Part 1*, Vol. 392, No. 2, 1992, pp. 760-765.
- [2] D.M. Smith, G.J. Hurford, and S.E. Boggs, "Rotating Modulation Collimator Imagers", *New Astronomy Reviews*, Vol. 48, No. 1, 2004, pp. 209-213.
- [3] A. Das, B. Sur, S. Yue, and G. Jonkmans, "Inverse Collimator-Based Radiation Imaging Detector System", *AECL Nuclear Review*, Vol. 1, No. 1, 2012, p. 61.
- [4] S. Kronenberg, G.J. Bruckner, E. Bechtel, and F. Gentner, "Directional Detector for Array of Gamma Ray and X-Ray Sources", *Nucl. Instr. and Meth. in Phys. Research*, v. A378, 1996, p. 531.
- [5] P.T. Durrant, M. Dallimore, I.D. Jupp, and D. Ramsden, "The Application of Pinhole and Coded Aperture Imaging in the Nuclear Environment", *Nucl. Instr. and Meth. in Phys. Research*, Vol. A422, 1999, p. 667-671.
- [6] S.V. Guru, Z. He, D.K. Wehe, G.F. Knoll, R.H. Redus, and M.R. Squillante, "Portable High Energy Gamma Ray Imagers", *Nucl. Instr. and Meth. in Phys. Research*, Vol. A378, No. 3, 1996, p. 612.
- [7] O. Gal, M. Gmar, O.P. Ivanov, F. Laine, F. Lamadie, C. Le Goaller, C. Mahe, E. Manach, and V.E. Stepanov, "Development of a Portable Gamma Camera with Coded Aperture", *Nucl. Instr. and Meth. in Phys. Research*, Vol. A 563, 2006, p. 233-237.
- [8] A. Macleod, P. Boyle, D. Hanna, P. Saull, H. Seywerd, and L. Sinclair, "All-Scintillator Compton Gamma Imager", *Physics in Canada*, Vol. 65, No. 3, 2009, p. 134.