A hybrid camera for locating sources of gamma radiation in the environment

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ABSTRACT: We present a new concept for a portable environmental imaging system, the Compact Hybrid Gamma Camera (CHGC). This combines an optical and a gamma-photon camera in a co-aligned configuration that offers high spatial resolution multi-modality imaging for superposition of gamma ray and optical images. We report on its potential use for surveying, monitoring and clean-up of radioactive sources in the environment.

KEYWORDS: Radiation monitoring; Inspection with gamma rays
1 Introduction

Monitoring of radiation in the environment as part of radiation protection and security is an important and expanding area of research. New techniques and innovative detection systems are currently in development [1]–[3]. Gamma cameras can play an important role in monitoring radioactive waste containers, visually identifying contamination in industrial or medical environments, and in nuclear facility maintenance or decommissioning [1]–[11].

All gamma cameras share a number of common features: collimators (pinholes, parallel hole arrays or slats), a conversion medium — normally a scintillator or a semiconductor, and a readout mechanism — either Photomultiplier Tubes (PMTs) or semiconductor arrays. The parameters governing the camera design are driven by the required Field of View (FOV), sensitivity, spatial resolution, portability, cost and intended working environment [1]–[11].

The type of collimator chosen will ultimately be a compromise between sensitivity, spatial resolution and field of view. Baek et al. [8] stated that, although several types of collimator may be used in gamma cameras, a pinhole collimator is the most expedient for environmental imaging as it makes large area monitoring possible and offers the same angular resolution regardless of the distance between the source and the camera. However, the efficiency of pinhole collimators decreases rapidly with distance from the source and they can suffer from non-uniform spatial resolution across the field of view [12]. Although semiconductor devices can have extremely good energy resolution their stopping power can be a disadvantage at gamma ray energies used in environmental applications (typically 50 keV–1.5 MeV). Most cameras use scintillators to convert the high energy gamma photon to lower energy light which is then detected and analysed to give position and energy for the incident gamma photon although this increase in efficiency is at the expense of energy resolution [2–4, 8, 10].
Combining different imaging modalities has been pioneered in the medical imaging field where Positron Emission Tomography and Single Photon Emission Computed Tomography combined with Computed Tomography (PET-CT, SPECT-CT) are now well established in clinical use [13, 14]. Subsequent to this, the more recent development of PET and Magnetic Resonance Imaging (PET-MRI) has now entered clinical use [15, 16]. Such systems present the clinician with a range of images and functional information enabling them to achieve a more accurate and comprehensive diagnosis than would be possible using one modality alone. There have also been a number of researchers producing combined optical and gamma camera systems for use in medical and life science applications [17]–[19].

We have been developing a portable hybrid small field of view (SFOV) gamma camera for medical diagnostics [19, 20] with potential for applications in environmental monitoring and imaging. This communication describes a compact dual modality camera, the Compact Hybrid Gamma Camera (CHGC), that combines optical and gamma ray environmental imaging into a single system.

2 Compact Hybrid Gamma Camera

The Compact Hybrid Gamma Camera (CHGC) combines an optical and a gamma photon camera in a co-aligned configuration that offers high spatial resolution multi-modality imaging with a fused image output. The basic design is flexible, such that it can be adapted to a wide range of applications and used in a variety of environments. Figure 1 shows a schematic of the overall system; the hybrid camera head comprises a low profile optical system (mirror and camera) which is located in front of the collimator of the gamma camera both of which are connected to the readout and control electronics system all which are managed by a standard PC or laptop. Because of the low profile
design, gamma photons from the source will pass through the optics with minimal absorption and scatter (> 90% transmission at 140 keV).

The gamma camera consists of a charge coupled device (CCD), a CsI(Tl) scintillator coupled to the CCD and a tungsten pinhole collimator, the details of which have previously been reported [20]. The CCD to pinhole distance is fixed at 10 mm, therefore the distance from the pinhole to the object being imaged determines the magnification on the CCD. Gamma-ray photons arriving from the source will interact with the scintillator and generate optical photons which are subsequently detected by the CCD allowing the position and the energy of the incident gamma photon to be recorded [20]. The hybrid camera head is surrounded by tungsten shielding (3 mm thickness).

2.1 Imaging software

The imaging system was designed to operate in either single- or dual-modality mode. Both the optical and gamma images were displayed independently or in a fused co-aligned image with the contrast and colour tables adjustable to help interpretation.

Exposure times for a full gamma image could range from a few seconds to tens of minutes depending on the amount of activity of the source and the image contrast required. Typically a gamma image consists of 100–10,000 individual frames acquired over a period of time. The raw image is analysed on a frame by frame basis using a “blob-detection” algorithm with automatic scale selection [20]. This analysis approach gives information on the number and intensity of all the gamma interactions in the scintillator, which in turn provides information on the energy distribution of the gamma events. Energy window selection, based on the energy spectrum, can remove fluorescence X-rays and scattered photons from the final constructed image.

Optical images were captured directly from the optical system electronics using bespoke interface software which allows the concurrent capture of images from multiple cameras. Each image is imported directly into the main acquisition software for display and analysis. In the current configuration the optical cameras are simple off-the-shelf “web-cams” chosen for their low cost and availability.

When a combined, or fused, image is required the optical image forms the background on which the gamma-ray image is overlaid. Each pixel of the gamma-ray image is compared to the corresponding optical pixel. Simple scaling was used for pixel mapping and comparison algorithms are used to determine the final value of the corresponding pixel in the fused image. Each image type (optical, gamma or fused) can be saved in a number of different formats including TIFF and JPEG.

3 Results

3.1 Imaging phantoms

To explore the spatial resolution of the CHGC a number of different mini-phantoms were manufactured providing a variety of possible shapes and configurations [21]. In particular, to evaluate the combined optical/gamma configuration a cross phantom was precision engineered from Perspex at
Figure 2. Left: optical image of the cross hot-spot phantom. Centre: gamma-ray image of the phantom showing the five $^{99}$mTc filled holes. Right: combined optical and gamma image. Gamma image frames ($\sim$2 min exposure). Distance of phantom to CHGC system was 121 mm.

Figure 3. Scaling of images as a function of the object distance from camera face.

the Space Research Centre, University of Leicester. This phantom had 21 holes, each 2 mm in diameter, 4 mm depth, drilled in 5 mm thick Perspex with a nominal hole spacing of 10 mm covering an area of 80 mm $\times$ 80 mm.

Five of the holes were filled from a stock solution of $^{99}$mTc using a micropipette, giving a total activity of approximately 5 MBq. The phantom was imaged using both the optical and gamma camera at a number of different distances above the CHGC system. Figure 2 shows a photograph of the cross phantom held in a retort stand along with a gamma-ray image of the five filled holes and the fused optical/gamma image, the variation in gamma intensity being caused by differing fill levels in each hole of the phantom.

Scaling of images. Images from both cameras were taken with the phantom to camera system distance varying from $\sim$45 mm to 150 mm. The positions of the “hot spots” from the gamma ray image were scaled to match the position of the optical image. Figure 3 shows the relationship of
the scaling as a function of distance from the hybrid system. The effect of magnification was more prominent at shorter distances but became less significant as the source was moved away from the CHGC system. The largest uncertainty on the scaling factor comes from the measurement of the camera-to-source distance which we estimate to be around 5%. The hole-to-hole alignment was very good as can be seen in figure 2. Previously we have shown that the spatial resolution of the gamma camera was of the order $\sim 1.0$ mm FWHM [20]. Bugby et al. [22] have characterised the full response of the gamma camera using a newly developed protocol for small field of view gamma cameras [23] and reported a spatial resolution of $< 0.7$ mm FWHM for 140 keV photons at a distance of 10 mm from the collimator.

3.2 Environmental images

To assess the potential of the CHGC for use in environmental imaging a number of scenarios were created. The first of these was a simple test using three vials filled with known amounts of $^{99m}$Tc solution (with a small amount of red colouring) imaged at a range of distances and ambient light conditions. Figure 4 shows the three vials, the left one containing 78.5 MBq, the centre having 3.5 MBq and the right vial containing no radioactivity, sitting on a laboratory bench at a distance of 300 mm from the CHGC. The intensity scale is logarithmic to bring up the low activity vial against its very bright neighbour. It is clear we can image a relatively weak source in the vicinity of a comparably strong source, a prerequisite for any environmental imager. The extrinsic sensitivity for the Compact Hybrid Gamma Camera with the source at 13 mm is 214 cps/MBq. Unambiguous identification of the central vial, figure 4, within 2 minutes can be taken as the practical detection limit for the CHGC at the present time. A full report on the detection limits and the Contrast to Noise Ratio characteristics of the CHGC will be the subject of a future publication.

A second test of the system used a single vial filled with a known amount of $^{99m}$Tc solution and imaged at a range of distances and ambient light conditions. Figure 5 shows the vial, contain-
300 MBq of $^{99m}$Tc sitting on a laboratory bench at a distance of $\sim$2.5 m from the CHGC. It clear from the composite image that the location of the radioisotope was correctly identified and located. The initial location of the radioactive source could be identified within $\sim$250 seconds. For unambiguous location the source was imaged for $\sim$1000 seconds. At a distance of 2.5 m the spatial resolution of the gamma camera was approximately $\sim$11 cm FHWM which, for most applications seeking to identify the location of radioactive sources, should be sufficient. If the spatial resolution is not a limiting factor then a larger pinhole diameter may be fitted to the gamma camera (for example, a 1 mm diameter hole) which would increase the detection efficiency significantly and reduce the time of location.

Another potential application of a hybrid optic/gamma camera is in the identification of radioactive spills or contaminated items. To assess this scenario a number of items having a range of activities were placed in a metal tray. A piece of filter paper had a small area covered in a $^{99m}$Tc solution ($<0.5$ MBq), as did a standard laboratory glove.

In addition the syringe used to create these “sources” and the vial containing the stock solution ($\sim$300 MBq) were placed into the tray. Having a relatively high source of radioactivity (the vial), which was at least two orders of magnitude more active than the other items, enabled the assessment of the camera’s capability to identify weak sources alongside a significantly greater activity.

Figure 6 shows the fused optical and gamma images. Each of the radionuclide sources are clearly identified within the tray. The intensity scale was adjusted to bring out the low activity in
the filter paper (top left) which resulted in the size of the vial source appearing greater than one would expect. The accumulation time for the full gamma image was 100 seconds, driven by the activity of the weakest source.

4 Stereoscopic imaging

The hybrid camera concept can be extended to a two camera design which offers the potential for stereoscopic imaging with depth estimation of the gamma-emitting source.

Figure 7 shows a schematic of the overall system; the camera pair, in an arbitrary “stereo” configuration, viewing two objects, one containing a radioisotope labelled source. The two optical systems will sit in front of the collimators giving two independent images of the source.

In this dual hybrid camera configuration there is the potential for 4 independent images; two optical and two gamma-photon which can be displayed as individual images, as two combined optical-gamma images, or as a single combined stereo image.

To test the stereo imaging concept three small vials were filled with coloured solution and placed on a laboratory bench. The centre vial had small volume of $^{99m}$Tc solution added (activity of vial $\sim 3.5$ MBq)

Currently we have only one fully operational CHGC. However, to test the stereo imaging concept the vials were imaged after the CHGC was translated 30 mm perpendicularly to the objects and a second series of images of the vials were accumulated. Figure 8 B shows the fused images

![Combined optical and gamma image of a number of "radioactive" items.](image)
from our simple experiment. To achieve a stereoscopic effect one set of optical images were green filtered while the other was red filtered. This “classic” stereo image is shown in figure 8 (to see the stereo effect a pair of red/green glasses is required).

With more than one hybrid camera the potential to estimate the depth of the radioisotope distribution becomes a possibility. In the simplest case of the two hybrid camera configuration the position of the gamma source can be calculated from the known geometry of the camera system, their viewing angle with respect to the object, angular distance between each camera and the independent image from each hybrid system. Obviously extending the number of cameras would improve the position accuracy but at the expense of complexity and increased cost.

Recently there has been a huge drive to produce “glasses free” 3D image displays, mostly driven by the consumer TV market. Such devices, when fully realised, would obviously be ideal for stereo imaging — allowing the user to view the full stereo effect without the need for cumbersome glasses.

5 Conclusions

The successful detection and localisation of radionuclides in the environment can be enhanced by multi-modality imaging. A system that combines optical imaging with a small field of view gamma camera has the potential to enable detection in remote or difficult areas where portability and size are major concerns.

Pin-pointing radioactive sources is a major issue for many applications in the nuclear industry [24]. The use of the non-destructive technique offered by gamma imaging enables radioactive hot spots contained in a given area to be accurately located. Gamma cameras have been commer-
cialized by various companies but a number of requirements in terms of sensitivity, weight and ease of use still present limitations to the end-users [25, 26]. For example, some commercial cameras weigh as much as 20–24 kg [9]–[11, 27] and have relatively small (4°–18°) Field of View [11, 27].

The combination of a portable gamma camera with an optical camera will have many practical benefits in a number of applications such as contamination monitoring and nuclear decommissioning. The most obvious benefit is the ability to accurately localise the site of radionuclide contamination or spillage. We anticipate that providing the operators with an overlaid image during the exploratory phase will increase confidence of localisation of radioactive sites, give details of the object and reduce the procedure time. It is quite feasible that this type of imaging may be undertaken remotely, with the camera mounted on a motor driven kart thus reducing any potential exposure to individuals.

In summary a prototype hybrid camera has been designed and constructed. This system has shown to be capable of high resolution gamma imaging combined with optical imaging to produce fused images offering improvements in a number of environmental applications. The design of the current CHGC (weight approximately 1.5 kg with a 60° FOV) make it attractive in applications where portability and large FOVs are important.

The CHGC has been used to produce dual-modality images in simulations of a number of applications. In addition we have shown that the hybrid camera concept can be extended to produce stereoscopic imaging of both optical and gamma photons, which could be used to estimate the position (or depth) of radionuclide distribution within an environment or object.

The new hybrid, portable camera offers combined optical and gamma imaging that introduces new techniques to address both existing and emerging environmental needs.
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