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Remote Sensing of Neutron and Gamma Radiation using Aerial Unmanned Autonomous System

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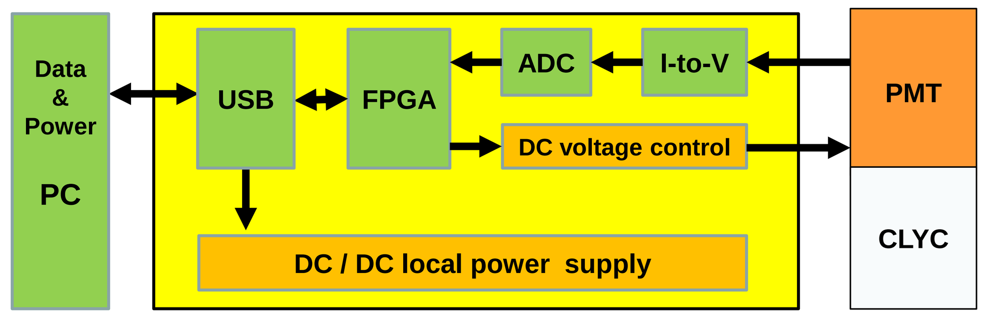
Introduction

- Nuclear technologies
  - Power generation plants
    - Research / nuclear facilities
      - Safe control of nuclear systems is vital
- One of the lessons learned from the Fukushima accident
  - The need for ubiquitous sensing capability in key facilities of the plant
  - It was found that the spent fuel pools of this plant were under-instrumented
    - Expert teams involved in the accident analysis recommended that inexpensive and easily implementable sensors are desired
      - With wireless control and data transmission
- To address the need for remote sensing of radiation in various nuclear applications
  - The system based on unmanned aerial vehicles (UAV) was designed
    - Radiation monitoring and mapping
      - Radiation source localization

Radiation Detector

- Low-power, 25mm × 25mm detector
- Elpasolite Cs_2LiYCl_6:Ce (CLYC) scintillator
- CLYC properties
  - Density: 3.31 g/cm^3
  - Refractive index: 1.81
  - Light-emission spectral range
    - 275 nm to 450 nm (the peak is at 370 nm)
  - Scintillation light yield
    - ~20,000 photons/MeV for gamma rays
    - ~70,000 photons/neutron for thermal neutrons

CLYC detector



- Small PMT
- Miniature eMorpho digitizer
  - 2.5″ by 2.5″ PCB
  - HV generator

Maximum Likelihood Estimation

- Maximum Likelihood Estimation (*MLE*) for the point-like source localization
- Signal intensity is observed simultaneously and cooperatively by multiple sensors
- Radioactive sources emitting gamma rays or neutrons of various energies will be located by a moving sensor or multiple sensors
- *PDF* depends on possible intensity and coordinates of the source (x_s, y_s):

$$L\left(x_s, y_s, I_0 \mid \{N_i\}_{i=1}^{n}\right) = \frac{1}{(2\pi)^{n/2}\prod_{i=1}^{n}\sigma_i} \times \exp\left(-\sum_{i=1}^{n}\frac{\left(N_i - {I_0}/{R_i^2}\right)^2}{2\sigma_i^2}\right)$$

$$R_i = \sqrt{(x_i - x_s)^2 + (y_i - y_s)^2}$$

distance between *i*-th detector and a source

- 2nd moment of the *normalized likelihood function L* represents the spatial resolution of the system:

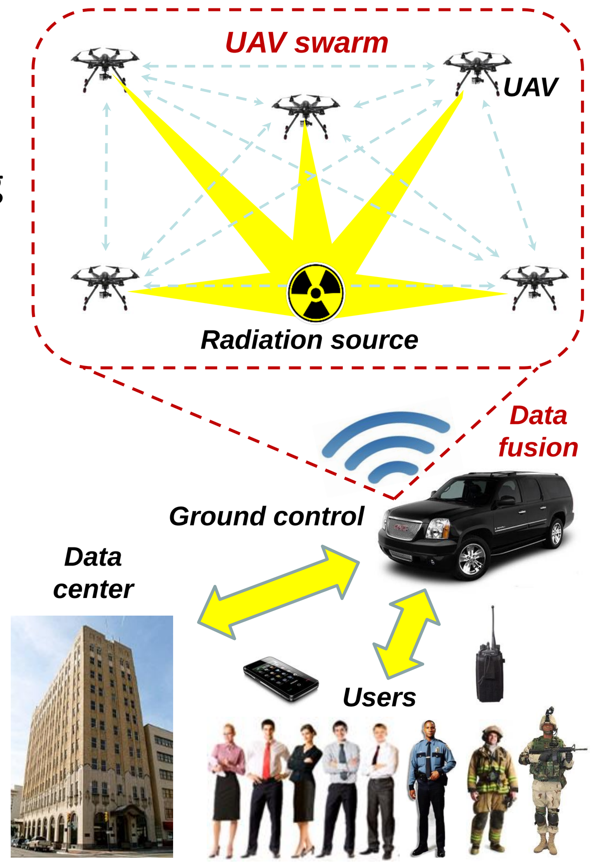
$$\bar{x}_s = \int x_s L\left(x_s, y_s, I_0 \mid \{N_i\}_{i=1}^{n}\right) dx_s dy_s dI_0$$

$$\bar{x}_s^2 = \int x_s^2 L\left(x_s, y_s, I_0 \mid \{N_i\}_{i=1}^{n}\right) dx_s dy_s dI_0$$

$\{N_i\}_{i=1}^{n}$ the set of *n* sensor's signals measured with accuracy σ_i and I_0 is the source intensity

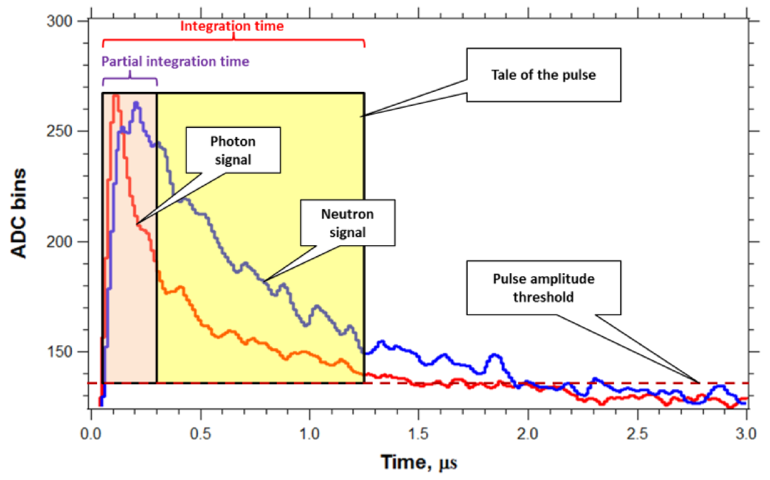
Monitoring Approach

- Technical approach to ubiquitous radiation monitoring:
  - To employ a swarm of low-cost, small-scale UAVs equipped with navigational and sensing capabilities
  - To perform the radiation surveillance in potentially radioactive locations
    - Which allows the measurements to be dynamically tracked and mapped
- Monitoring data could be used for analysis and prognostics
  - Temporal domain
    - Space domain
- Cooperative sensing algorithms:
  - The swarm of UAVs can be programmed
    - Search for unattended radiation sources



Digital Signal Analysis

- CLYC has scintillation properties and proportionality allowing ambient-temperature photon spectrometry
  - Energy resolution: 5% at 662 keV, 3.6% at 1173 keV, 3.3% at 1332 keV
- Neutron detection: $^6Li(n,\alpha)^3He$ reaction
- Neutron / photon pulse shape discrimination (PSD) properties
- Gamma-ray excitation
  - *Fast* core-to-valence luminescence (CVL): 1-ns decay constant
  - Ce^{3+} prompt emission: 50-ns decay constant
- Neutron excitation
  - *Slow* Cerium self-trapped excitation (Ce^{3+}-STE): 1000-ns decay constant

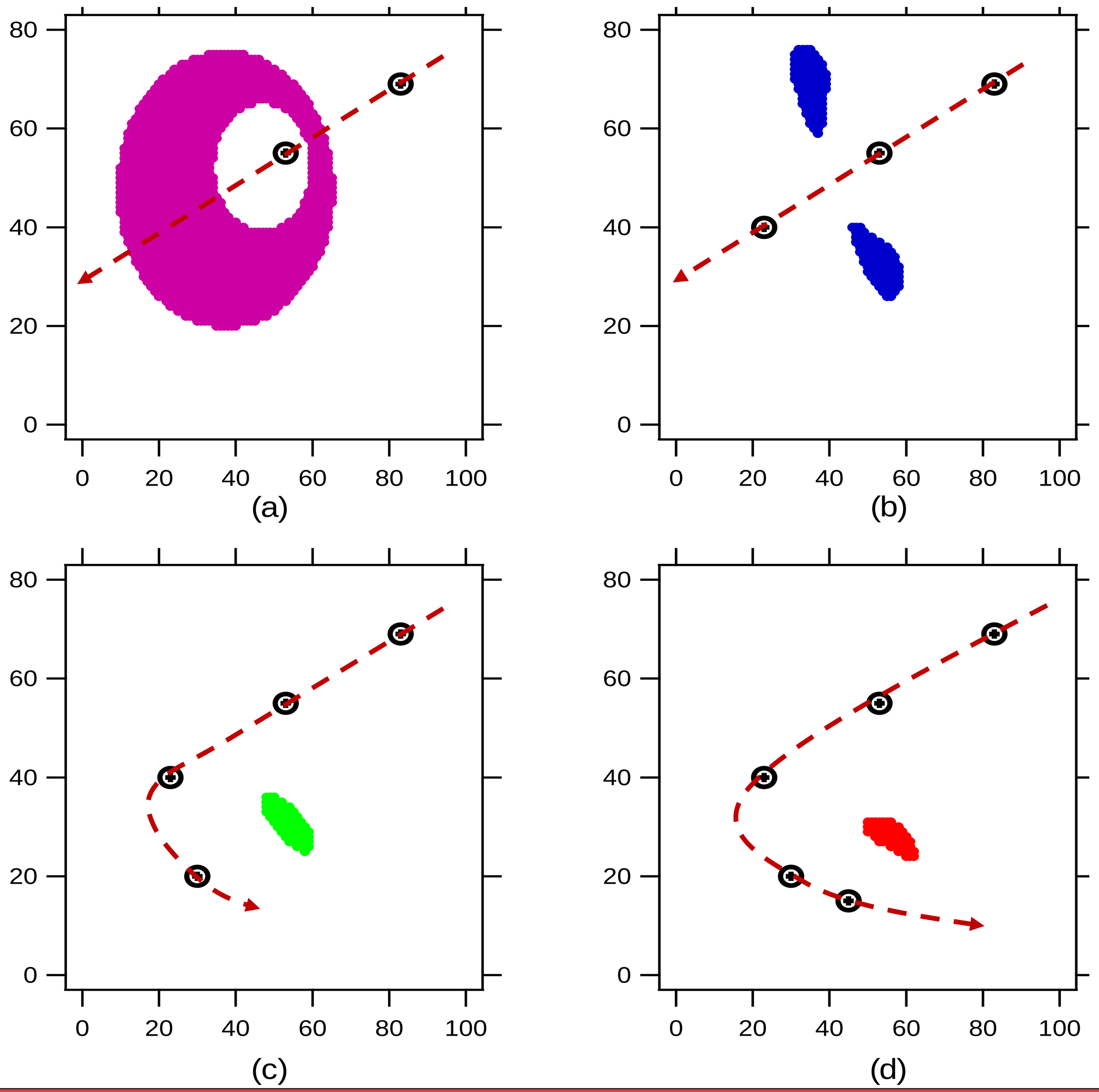


Digitized waveforms in the time domain

$$\text{PSD value} = \frac{\text{total integral} - \text{partial integral}}{\text{partial integral}}$$

- List mode
  - Partial integral
    - Energy (total integral)
      - Time stamp

Radiation Source Localization



Probability maps

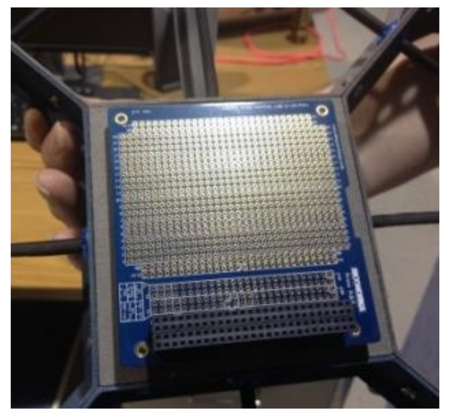
Computed for a source placed at a point with coordinates (55, 30)
(a) 2 sensors,
(b) 3 sensors,
(c) 4 sensors, and
(d) 5 sensors
measuring cooperatively (or single-UAV sensing points)

Areas where a radiation source with particular spectral lines can be found with the probability ≤ 68% are shown in color

UAV Platform

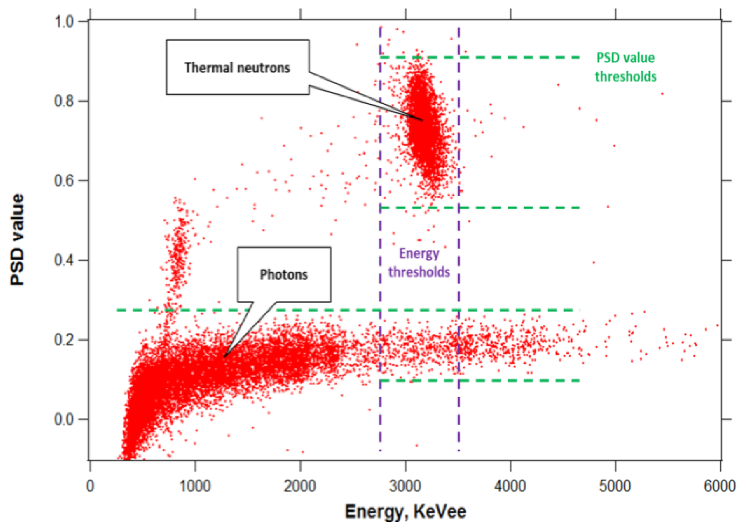
- Quadrotor from Skyworks Aerial Systems
- The UAV platform is small and versatile
  - Less than 20 inches wide
  - It can maneuver into tight spots (i.e., indoor areas)
    - Hazardous environment
- Compact radiation detector was integrated into the UAV platform
  - Using its communication and power interface
    - 5 V and 3.3 V lines
    - SPI, I2C, UART buses
- The ARM Cortex M4F onboard flight management unit enabled sending the data to a ground station or other UAVs via the 900-MHz telemetry radio
- The data included GPS coordinates of the point of measurement

UAV platform

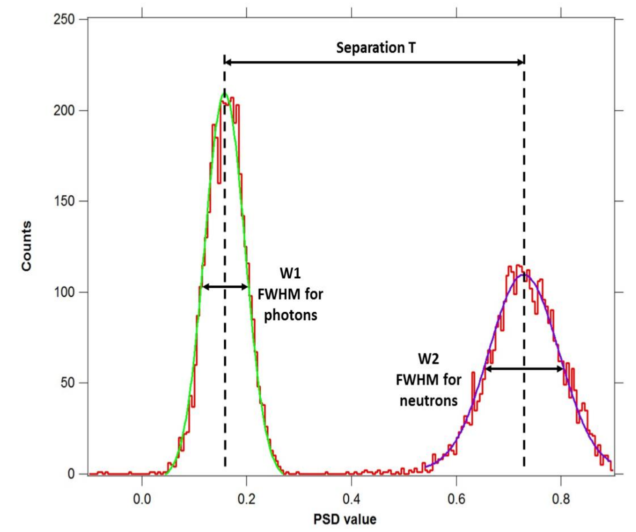


UAV interface board

Pulse Shape Discrimination



Neutron / photon PSD (PuBe source)



FOM = *T* / (W_1 + W_2)

- The 'on the fly' digital PSD enabled distinguishing waveforms
  - Generated by photon and neutron interactions with the scintillator
- Experiments showed neutron / gamma segregation properties of the detector
  - PuBe source
    - PSD figure of merit (*FOM*) ~ 2.3

Conclusion

- Small-scale UAV for remote sensing and monitoring of neutron and gamma radiation was designed
- Compact radiation detector was developed and tested in mixed neutron / photon radiation fields
- MLE method enables the source localization
- Mobile nature of the system allows radiation measurements to be performed at desired locations

Acknowledgement

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GPSA University of Nevada, Las Vegas