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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

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

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 Interface Board

Radiation Detector
- Low-power, 25mm × 25mm detector
- Elpasolite CsI(LiYCl₃:Ce) (CLYC) scintillator
- CLYC properties
  - Density: 3.31 g/cm³
  - 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/MeV for thermal neutrons
- Small PMT
- Miniature eMorpho digitizer
- 2.5” by 2.5” PCB
- HV generator

CLYC detector

Digital Signal Analysis
- CLYC has scintillation properties and proportionality allowing ambient-temperature photon spectrometry
  - Energy resolution: 5% at 662 keV, 3.6% at 1373 keV, 3.3% at 1332 keV
- Neutron detection: (Li(n,α)He) reaction
- Neutron / photon pulse shape discrimination (PSD) properties
- Gamma-ray excitation
  - Fast core-to-valence luminescence (CVL): 1-ns decay constant
  - Ce³⁺ prompt emission: 50-ns decay constant
- Neutron excitation
  - Slow Cerium self-trapped excitation (Ce³⁺-STE): 1000-ns decay constant

Pulse Shape Discrimination
- 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
- Pulse source
- PSD figure of merit (FOM) ~ 2.3

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 (xᵢ, yᵢ):
  \[ \frac{1}{\Delta x \Delta y} \sum_{i=1}^{n} \left( \frac{W_i}{\lambda_i^2} \right) \exp \left( -\frac{|x_i - x|}{\lambda_i} - \frac{|y_i - y|}{\lambda_i} \right) \] where \( \Delta x, \Delta y \) is the set of n sensor’s signals measured with the same accuracy \( σ \), and \( i \) is the source intensity

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

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

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