Hyperspectral technology: inspiring ideas, challenges and opportunities

José López-Feliciano/Roberto Sarmiento
Institute for Applied Microelectronics (IUMA)

Part I: Introduction
Part II: HPC on-board Satellites
Part III: Our projects using HSI technology
Hyperspectral technology: inspiring ideas, challenges and opportunities

Part I: Introduction

José López-Feliciano/Roberto Sarmiento
Institute for Applied Microelectronics (IUMA)
Outline

• The institute for Applied Microelectronics at ULPGC
• Why hyperspectral technology?
  • Some numbers
  • Applications
• Introduction to hyperspectral technology
  • The human eye
  • Multi- vs hyperspectral sensors
  • Types of hyperspectral sensors
• Ongoing projects
  • Space
  • Precision agriculture
  • Environment
  • Health
Outline

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• Why hyperspectral technology?
  • Some numbers
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• Introduction to hyperspectral technology
  • The human eye
  • Multi- vs hyperspectral sensors
  • Types of hyperspectral sensors

Part I

• Ongoing projects
  • Space
  • Precision agriculture
• Environment
• Health

Part II

Part III
The Institute for Applied Microelectronics at ULPGC

29/06/2023
The Institute for Applied Microelectronics at ULPGC

CANARY ISLANDS
- POPULATION: 2,2 million
- % FOREIGNERS: 13%
- TOURISTS: 13 million/yr

AVERAGE: 21 ºC
WINTER: 18 ºC
SUMMER: 24 ºC
The Institute for Applied Microelectronics at ULPGC

<table>
<thead>
<tr>
<th></th>
<th>CANARY ISLANDS</th>
<th>ICELAND</th>
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<tbody>
<tr>
<td>POPULATION</td>
<td>2.2 million</td>
<td>0.38 million</td>
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<tr>
<td>% FOREIGNERS</td>
<td>13%</td>
<td>24%</td>
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<tr>
<td>TOURISTS</td>
<td>13 million/yr</td>
<td>5.7 million/yr</td>
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</table>
The Institute for Applied Microelectronics at ULPGC

TWO PUBLIC UNIVERSITIES:

Univ. Las Palmas de Gran Canaria (aprox. 20,000 students)

Univ. La Laguna (aprox. 23,000 students)

FOUR PRIVATE UNIVERSITIES:

Universidad del Atlántico Medio
Universidad Fernando Pessoa
Universidad de Las Hesperides
Universidad Europea de Canarias
The Institute for Applied Microelectronics at ULPGC

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The Institute for Applied Microelectronics at ULPGC

DIVISIONS

Integrated Systems Design, ISD
Communication Systems, COM
Maths, Graphics and Computation, MAGIC
Microelectronics and Microsystems, MEMS
Industrial Systems and CAD Tools, SICAD
Information Technology, TI
Microelectronic Technology, TME

FEATURES

More than 130 researchers
More than 200 R&D projects
The Institute for Applied Microelectronics at ULPGC
Why hyperspectral technology?

Hyperspectral Imaging Systems Market Size, 2021 to 2031 (USD Billion)
Why hyperspectral technology?
Why hyperspectral technology?
Why hyperspectral technology?
Why hyperspectral technology?

Emerging Applications of Hyperspectral Imaging

- Agriculture
- Ocean Analysis
- Medical Diagnosis
- Environment Analysis
- History & Archaeology Conservation
- Food Safety & Control
- Surveillance & Security
- Fruit Quality Inspection
- Mineral Mapping
- Document Forgery
Introduction to hyperspectral technology

Human Eye Anatomy

- Sclera
- Iris
- Cornea
- Pupil
- Lens
- Ciliary body and muscle
- Conjunctiva
- Retina
- Optic nerve
- Macula
- Retinal blood vessels
- Vitreous body
Introduction to hyperspectral technology

**STEP 1**  Light rays enter the eye through the cornea

**STEP 2**  The iris changes the size of the pupil from very small to large in order to regulate the amount of light that is entering

**STEP 3**  It continues through the lens and passes through the largest part of the eye filled with a jelly-like substance called vitreous body

**STEP 4**  The light finally reaches the retina, the membrane at the back wall of the eye which contains photoreceptors

**STEP 5**  The photoreceptors converts light into electrical signals which travel to the brain
Introduction to hyperspectral technology

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Introduction to hyperspectral technology

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Introduction to hyperspectral technology

**RODS**
Responsible of visión at low level light
Scotopic visión
Aprox. 100 million

**CONES**
Contain photopigments
Active at higher light levels
Photopic visión
Perception of color
Aprox. 7 million
Three types: L (red)
S (blue)
M (green)

The proportion of the light recognized by these three cone types is interpreted by the brain, determining the colors
Introduction to hyperspectral technology

- **RED**: 620-720 nm
- **GREEN**: 500-570 nm
- **BLUE**: 460-500 nm
Introduction to hyperspectral technology

- Increasing Frequency (ν)

- Increasing Wavelength (λ)
Introduction to hyperspectral technology

The electromagnetic spectrum from high energy to low energy, showing the different regions such as gamma rays, X-rays, UV, IR, microwave, AM radio waves, and long radio waves. The spectrum is ordered by increasing frequency and decreasing wavelength.
Introduction to hyperspectral technology

- Increasing Frequency ($\nu$)
  - $10^{24}$ to $10^{0}$
- Increasing Wavelength ($\lambda$)
  - Visible spectrum
  - $400$ to $700$ nm
Introduction to hyperspectral technology

RGB

Multispectral

Hyperspectral

Intensity

Wavelength

Intensity

Wavelength

Intensity

Wavelength

29/06/2023
Introduction to hyperspectral technology
Introduction to hyperspectral technology

![Graph showing surface reflectance across different wavelengths for various materials like Cloud, Water, Dry grass, Vegetation, and Snow.]
Introduction to hyperspectral technology
Introduction to hyperspectral technology
Introduction to hyperspectral technology

Seeing the invisible
HYPERSPECTRAL IMAGING SENSOR

FOCAL PLANE ARRAY OF CAMERA

FOCUSING OPTICS/CURVED MIRRORS

HIGH-PERFORMANCE GRATING

FORE-OPTIC/LEN

ENTRANCE PORT WITH SLIT
Introduction to hyperspectral technology

WHISKBROOM SCANNING
- Captures one single pixel at a time
- Very high spectral resolution

PUSHBROOM SCANNING
- Captures one line at a time
- Very high spectral resolution

SPECTRAL SCANNING
- Entire spatial information for all bands at a time
- Produces cubes slowly

SNAPSHOT SCANNING
- Fast for moving objects
- Limited spectral and spatial resolution
Introduction to hyperspectral technology

Specim FX10 camera series is designed for industrial and laboratory use. Specim FX10 cameras work in a line-scan mode in the visible and near-infrared (VNIR) area; Specim FX10 in the 400-1000 nm region, and the color optimized Specim FX10c camera in the 400-780 nm region.

Specim FX10 cameras are best suited for:
• Vegetation & agriculture
• Phenotyping
• Color & density in printing
• Display & light source inspection
• Food quality

- Spectral range of 400-1000 / 400-780 nm
- High spatial resolution of 1024 pixels
- High image speed of 330 FPS (full range)
- Free wavelength selection from 224 bands within the camera coverage
- Built-in image correction
- Unified spectral calibration between units
- GigE or CameraLink standard interfaces
- Easy mounting to industrial environment

SPECTRAL RESPONSE

![Spectral Response Graph]

Wavelength (nm)

DN / Spectral radiance

400 500 600 700 800 900 1000
Introduction to hyperspectral technology

Specim FX17 camera is designed for industrial and laboratory use. It works in a line-scan mode, and collects hyperspectral data in the near-infrared (NIR) region (900 to 1700 nm).

Specim FX17 is best suited for:
- Food & feed quality
- Waste sorting
- Recycling
- Moisture measurement
- Threat detection, Security

- Spectral range of 900-1700 nm
- High spatial resolution of 640 pixels
- High image speed
  - 670 FPS (full range) for GigE version
  - 527 FPS (full range) for CameraLink version
- Free wavelength selection from 224 bands within the camera coverage
- Built-in image correction
- Unified spectral calibration between units
- GigE or CameraLink standard interfaces
- Easy mounting to industrial environment

**SPECTRAL RESPONSE**

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>DN / Spectral radiance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>1100</td>
</tr>
<tr>
<td>1200</td>
<td>1300</td>
</tr>
<tr>
<td>1400</td>
<td>1500</td>
</tr>
<tr>
<td>1600</td>
<td>1700</td>
</tr>
</tbody>
</table>

DX / Spectral radiance

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>DX / Spectral radiance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>1100</td>
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<td>1400</td>
<td>1500</td>
</tr>
<tr>
<td>1600</td>
<td>1700</td>
</tr>
</tbody>
</table>
Introduction to hyperspectral technology

Headwall's hyperspectral sensors deliver aberration-corrected imaging characterized by high spatial and spectral resolution, a wide field of view, and very high signal throughput. Headwall's own application-specific diffraction gratings are fundamental to these key specifications, which are crucial for airborne hyperspectral sensors. Headwall's all-reflective, concentric sensor design is robust and thermally stable.

### Hyperspec® SWIR

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Wavelength Range (nm)</td>
<td>900-2500</td>
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<tr>
<td>Aperture</td>
<td>F/2.0</td>
</tr>
<tr>
<td>Entrance Slit Width</td>
<td>25 μm</td>
</tr>
<tr>
<td>Dispersion/Pixel (nm/pixel)</td>
<td>6</td>
</tr>
<tr>
<td>FWHM Slit Image</td>
<td>6.3 nm</td>
</tr>
<tr>
<td>Slit Length</td>
<td>12 mm</td>
</tr>
<tr>
<td>Spectral Resolution</td>
<td>12 nm</td>
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<tr>
<td>Spectral Bands</td>
<td>267</td>
</tr>
<tr>
<td>Spatial Bands</td>
<td>384</td>
</tr>
<tr>
<td>Smile - Aberration-corrected</td>
<td>Yes</td>
</tr>
<tr>
<td>Keystone - Aberration-corrected</td>
<td>Yes</td>
</tr>
<tr>
<td>Detector</td>
<td>Stirling-cooled MCT</td>
</tr>
<tr>
<td>Max. Frame Rate (Hz)</td>
<td>450</td>
</tr>
<tr>
<td>Pixel Pitch</td>
<td>24 μm</td>
</tr>
<tr>
<td>Read A/D</td>
<td>16 Bit</td>
</tr>
<tr>
<td>Camera Control Interface</td>
<td>Base CameraLink and RS232</td>
</tr>
<tr>
<td>Weight (lb / kg)</td>
<td>9.6 / 4.4</td>
</tr>
<tr>
<td>Max. Power (W)</td>
<td>14.4</td>
</tr>
</tbody>
</table>

For more information contact:
analytik Ltd (UK and Ireland Distributor)
2 Cygnus Business Park, Middle Watch, Swavesey, Cambridge, CB24 4AA
T: +44 (0)870 991 4044
E: info@analytik.co.uk
www.analytik.co.uk
Introduction to hyperspectral technology
Introduction to hyperspectral technology
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Introduction to hyperspectral technology

MAIN CHALLENGES

• Applications
• Compression
• Unmixing
• Reducing prices
Introduction to hyperspectral technology

MAIN CHALLENGES

- Applications
- Compression
- Unmixing
- Reducing prices

- Specially for on-board applications (i.e. satellites, drones…)
- Reduce the on-board memory requirements
- Communication channel capacity restrictions
- Reduce download time
- Lossless vs. Lossy vs. Near lossless compression
- Spatial and spectral correlation
- CCSDS-123
Introduction to hyperspectral technology

MAIN CHALLENGES

- Applications
- Compression
- Unmixing
- Reducing prices

- Spectral unmixing is normally the first step in the analysis
- Pixels consist of a mixture of several materials
- Pure materials are named endmembers
- Abundances give the percentage of endmembers in a pixel
Introduction to hyperspectral technology

MAIN CHALLENGES

- Applications
- Compression
- Unmixing
- Reducing prices

- Multispectral cameras have lower prices
- DIY cameras
Introduction to hyperspectral technology
Hyperspectral technology: inspiring ideas, challenges and opportunities

Part II: HPC on-board Satellites

José López-Feliciano/Roberto Sarmiento

Institute for Applied Microelectronics (IUMA)
Outline

• Satellites for Earth Observation and Spacecrafts
• Satellites on-board Hardware
  • System overview
  • Payload hardware
• Technology solutions for on-board HPSC
  • Radiation effects mitigation
  • FPGAs - MPSoCs
• On-board Satellite payload data processing
  • New paradigm?
  • Data and Image Compression
  • Video Compression
  • Information Processing
• Conclusions
Satellites for Earth Observation and Space Crafts

- **Satellites**
  - Low Earth Orbit (LEO)
  - Medium Earth Orbit (MEO)
  - Geosynchronous (GSO) & Geostationary (GEO)
  - Highly Elliptical Order (HEO)

**Satellites by application**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth Observation (EO)</td>
<td>58%</td>
<td>50%</td>
</tr>
<tr>
<td>Scientific</td>
<td>26%</td>
<td>16%</td>
</tr>
<tr>
<td>Technology</td>
<td>12%</td>
<td>10%</td>
</tr>
<tr>
<td>Communications</td>
<td>4%</td>
<td>22%</td>
</tr>
<tr>
<td>Novel applications</td>
<td>0%</td>
<td>3%</td>
</tr>
</tbody>
</table>

Source: spaceaware.io

Iridium 119 (October 9, 2017) [783.2 / 786.3 km] Period: 100.4 minutes
Satellites for Earth Observation and Space Crafts

- Satellites and debris
  - PL Payload
  - PF Payload Fragmentation Debris
  - PD Payload Debris
  - PM Payload Mission Related Object
  - RB Rocket Body
  - RF Rocket Fragmentation Debris
  - RD Rocket Debris
  - RM Rocket Mission Related Object
  - UI Unidentified

- Satellites
  - Commercial use satellites in low orbit has an exponential grow
  - Increase demand of low-cost systems for high-performance space computing (HPSC) and communications using commercial hardware
  - New era of remotely sensed big data!!
Satellites for Earth Observation and Space Crafts

• Processing on-board is becoming mandatory

• From typical processing …
  • Radiation correction
  • Geometric correction
  • Calibration
  • Compression

• … to advanced processing:
  • Target detection
  • Classification
  • Cloud detection
  • Extract regions of interest (RoI) or crops of the scene
  • Artificial Intelligence

• “Satellite information services are moving from large-scale ground stations to on-vehicle, onboard, and hand-held terminals for receiving and transforming”

Outline

• Satellites for Earth Observation and Spacecrafts

• **Satellites on-board Hardware**
  • System overview
  • Payload hardware

• Technology solutions for on-board HPSC
  • Radiation effects mitigation
  • FPGAs - MPSoCs

• On-board Satellite payload data processing
  • New paradigm?
  • Data and Image Compression
  • Video Compression
  • Information Processing

• Conclusions
Satellite Hardware: system overview

- ESA SAVOIR (Space AVionics Open Interface aRchitecture)
- Complex but solved: modular solution
Satellite Hardware: system overview

- ESA SAVOIR (Space AVionics Open Interface aRchitecture)
- Complex but solved: modular solution
- High Performance Computing in Space??

Advanced Data Handling Architecture Modules Products (ADHA-MP):
- ADHA On-Board Computer Module (AOBCM)
- ADHA Mass Memory Module (A3M)
- ADHA Computing Modules (supporting Artificial Intelligence)
- ADHA Generic I/O Module (RTU/ICU modules)
- ADHA Specific I/O Module for AOCS sensors & actuators
- ADHA Specific I/O Module for propulsion valves
- ADHA Data Processing Modules
- ADHA Motor Drive Electronic Modules
- ADHA Security Modules for PF and/or
Satellite Hardware: payload processing

- Acquisition system:
  a) Fore-optics (telescope, slit assembly, and possibly depolarizer, etc.),
  b) Optis for VNIR, SWIR spectrometers and possibly a panchromatic (PAN) channel,
  c) Sensors (focal plane arrays, FPA) and their proximity electronics (PEs),
  d) An onboard calibration unit,
  e) A service module,
  f) Temperature sensors, heaters, etc.

- Processing system
  a) PFCU: A processing formatting and control unit
  b) MMU: A solid-state mass memory unit
Satellite Hardware: payload processing

- **Detector cooling**
- **Fore optics**
  - SWIR Spectr.
  - VNIR Spectr.
  - PAN Optics
- **Shutter**
- **Service module**
- **Temp Sensor**
- **Heater**

**Payload processing**

- **Lossless/ Near-lossless Compression**
- **Process, Format and Route**
- **Encryption**
- **Command & Telemetric**
  - Timing generation
  - OCXO
- **Payload Controller**
- **MMU control and monitor**
- **Downlink transmission control and monitor**
- **Telemand (TC) Telemetric (TM)**
- **Transmitter**
- **Power**

**MMU**
- **Mass Memory Unit**

**Ancillary Data**

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Satellite Hardware: payload processing

PFCU

Lossless/ Near-lossles Compression

Process, Format and Route

Data1 link

Data2 link

DataN link

Control inter.

Payload Controller

Encryption

Ancillary Data

Command & Telemetric

MMU control and monitor

Downlink transmission control and monitor

OCXO

Power

OCXO

Power

Telecommand (TC)

Telemetric (TM)

Trans- mitter

Downlink

Timing generation

Mass Memory Unit

Cover & Calibration Unit

FPGA

Temperature Sensor

Heater
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Radiation effects mitigation

Classification of Radiation Effects

Soft Error
- Single Event Effects (SEE)
  - Triggered by deposited energy from charged particles traversing through electrical devices.
  - Temporary “bit-flip” in memory element caused by internal charge deposition (1 changes to 0 and vice versa).
  - Can be recovered by power cycling. Temporal Effect.

Hard Error
- Permanent errors

Single Event Upset (SEU)
- Transient current or voltage spike. If propagated and latched by memory element, may result in “bit-flip”.
- Total Ionizing Dose (TID) effects
- Can be recovered by power cycling.

Single Event Transients (SET)
- Excessive current flow induced by sufficient energy from a charged particle and consequently to a permanent loss of device functionality.

Single Event Latch up (SEL)
- Total sum of radiation hitting the target component.

Rad Hard

Rad Tolerant

Temporal Effect.
- Hardware degradation and/or damage

High Performance and Disruptive Computing in Remote Sensing

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Technology solutions for on-board HPSC

- The computing power of typical on-board computers is strongly limited by the volume, power and mass of nanosatellites.

**µProcessors/µControllers**

It focuses on computation, requires peripheral ICs, supports fast generic computation, and has typical power consumption higher than 10 Watt.

**FPGAs**

It is a Re-programmable logic, has IP-cores for specific and complete micro-controllers, provides fast and low power for specific functions, has higher power than micro-controllers.

**ASICs**

It is a complete hardware solution for specific application, supports IP-cores for specific function, and has fast and power efficiency.

**MP-SOCs**

It provides a complete hardware and generic application. It has the smallest complete systems.

---

OBDH

Hardware of the satellite on-board Data Handling computing platforms

**NGMP/GR740**
Cobham Gaisler /ST/E2V/ESA

**AT697 LEON2FT**
(Atmel, 180nm)

**VT65**
(ST, 65nm)

**CWICOM**
(Atmel, 180nm)

**NGMP/GR740 (ST, 65nm)**

**ATF280F (Atmel, 180nm)**

**BRAVE-medium (ST, 65nm)**

**RTG4™**

**Kintex™UltraScale™ XQRKU060**

**NanoXplore NG-Ultra**

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High Performance and Disruptive Computing in Remote Sensing
Technology solutions for on-board HPSC: FPGAs

- Programmable logic to provide configurability to the system:
  - SRAM technology:
    - The most used
    - Non-permanent
    - Reconfigurability
    - No radiation hardness

- Antifuse technology
  - Permanent
  - Radiation hardness
  - One Time Programmable (OTP)
  - Best performance

- FLASH memory
  - Permanent
  - Reprogrammable
  - Medium radiation hardness
FPGAs

Example FPGA: Rad Tolerant

Xilinx® Radiation Tolerant (RT) Kintex® UltraScale™ XQRKU060 FPGA

- 20 nm technology
- Key advantages of RT Kintex UltraScale:
  - True Unlimited On-Orbit Reconfigurable Solution
  - >10X DSP Compute increase for Processing Intensive Algorithms & Analytics
  - Full Radiation Tolerance across All Orbits
  - 331K 6-inputs LUTs; 2760 DSPs.
  - MicroBlaze™ processor technology, fault tolerant, fail-safe, 32-bit RISC CPU, which can be instantiated within the FPGA.
  - This soft IP achieves a performance above 300MHz
  - Requires approximately 7,400 LUTs and 6,400 flip-flops
  - Has been implemented using a TMR

<table>
<thead>
<tr>
<th>Radiation Hardness</th>
<th>Virtex-4QV XQRV4QV</th>
<th>Virtex-5QV XQRV5QV</th>
<th>RT Kintex UltraScale XQRKU060</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process (nm)</td>
<td>Tolerant</td>
<td>Hard</td>
<td>Tolerant</td>
</tr>
<tr>
<td>Memory (Mb)</td>
<td>90</td>
<td>65</td>
<td>20</td>
</tr>
<tr>
<td>System Logic Cells (K)</td>
<td>55 to 200</td>
<td>131</td>
<td>726</td>
</tr>
<tr>
<td>CLB Flip-Flops (K)</td>
<td>49.1 to 176.1</td>
<td>81.9</td>
<td>663</td>
</tr>
<tr>
<td>CLB LUTs (K)</td>
<td>49.1 to 176.1</td>
<td>81.9</td>
<td>331</td>
</tr>
<tr>
<td>Transceivers</td>
<td>None</td>
<td>18 at 3.125Gb/s</td>
<td>32 at 12.5Gb/s</td>
</tr>
<tr>
<td>User I/O</td>
<td>640 to 960</td>
<td>836</td>
<td>620</td>
</tr>
<tr>
<td>DSP Slices</td>
<td>32 to 192</td>
<td>320</td>
<td>2,760</td>
</tr>
</tbody>
</table>
FPGAs - MPSoCs

- 28 nm STMFD20 process technology.
- On-chip thermal monitoring capability.

Processors

- A full System-On-Chip (SoC) based on a quad-core ARM Cortex R52.

FPGAs

- 4-Input Look-up tables (536928 LUTs).
- LUT expander to support up to 16 bits boolean functions.
- Advanced interconnect network to support random logic and coarse grain block functions.
- DSP Blocks for complex arithmetic operations (1344 DSPs).
- User memories with variable width and depth.
- Configuration modes: Master Serial SPI (Single, Sequential, TMR), SpaceWire.
- Dedicated low skew distribution network for clock, reset and load enable signals.

Interfaces

- Integrated Space Wire interface available for user applications.
- Multiple I/O powering support from 1.2V to 3.3V.
- Embedded logic to support DDR2, DDR3 and DDR4.

Radiation Tolerance

- Radiation hardening by design in configuration memories and registers.
- SEU immune up to LET > 60 MeV.cm2/mg.
- Total ionizing dose > 50 krad (Si).
- Embedded EDAC for user memory mitigation.
- Embedded configuration memory scrubbing.
- Fast automatic memory configuration repair.
- Embedded bitstream integrity check (CMIC).

Example MPSoC: Rad hard

NanoXplore NG-ULTRA: European FPGA

High Performance and Disruptive Computing in Remote Sensing
Radiation effects mitigation

- Possibility to use COTS in many of LEO missions.
- But SEU errors are possible.
- Techniques to mitigate this errors:
  - Hardware Triple Module Redundancy (TMR) or Double Module Redundancy (DMR).
  - Software processing in two processors at the same time
  - Error Correction and Detection with Memories.
  - Memory scrubbing.
- Xilinx provides Soft Error Mitigation (SEM) IP:
  - Enhanced correction capabilities, essential bits monitoring and fault injection for validation.

FPGAs – MPSoCs

Example MPSoC: COTS HPSC

- Based on Zynq Ultrascale+
- XCZU4CG-2LE-I (low power, industrial temperature range).
  - 2 ARM Cortex-A53 up to 1.5 GHz for computing
  - 2 ARM Cortex-R5 up to 600 MHz for Real-Time.
  - NEON engine is a specialized vector processing engine.
  - 1 GB of DDR4-2400 with EDAC.
  - Programmable logic.
- External PS interfaces: I²C, SPI, CAN, RS-485, UART
Outline

• Satellites for Earth Observation and Spacecrafts
• Satellites on-board Hardware
  • System overview
  • Payload hardware
• Technology solutions for on-board HPSC
  • Radiation effects mitigation
  • FPGAs - MPSoCs
• On-board Satellite payload data processing
  • New paradigm?
  • Data and Image Compression
  • Video Compression
  • Information Processing
• Conclusions
## On-board Satellite payload data processing

### Digital processing on-board

- Calibration.
- Compression.
- Object detection.
- etc.

### It is different in space? Yes!!!

- High processing power.
- Different missions: different objectives.
- Difficulties to adapt to different payloads, requiring custom solution.
  - i.e.: Earth observation vs. debris detection.

### Space standards

- CCSDS standards.

### Lack of testing data

### HPSC: High Performance Space Computing

- It is hard to achieve onboard real-time processing without systematic optimization design for specific targets.

  "The key to a breakthrough is the development of new computing architectures, such as information extraction algorithms for non strict quantitative data processing". *

- Cross-level collaboration architectures of algorithm-software-hardware is required.
  - Heterogenous Computing.

### Two examples:

- Adaptative compression based on cloud removal
- IA for object detection and tracking.

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On-board Satellite payload data processing

Copernicus HPCM (High Priority Candidate Missions)
CHIME (Copernicus Hyperspectral Imaging Mission For The Environment)

The CHIME mission aims to augment the Copernicus space component with precise spectroscopic measurements to derive surface characteristics in support of the monitoring, implementation and improvement of policies in the domains of raw materials, agriculture, soils, food security, biodiversity, environmental degradation and hazards, inland and coastal waters, snow, forestry and the urban environment.

Example 1

Volcanic Eruption at the Krýsuvík-Trölladyngja volcanic system, Iceland. This image, acquired by one of the Copernicus Sentinel-2 satellites on 23 March 2021, shows the volcanic eruption in Iceland’s Reykjanes peninsula.

Volcanic Eruption in La Palma, Canary Islands, Spain. This Image acquired by one of the Copernicus Sentinel-2 satellites on 10 October 2021, shows the lava stream from the Cumbre Vieja volcano.
On-board Satellite payload data processing

**Copernicus HPCM (High Priority Candidate Missions)**
**CHIME (Copernicus Hyperspectral Imaging Mission For The Environment)**

- **System requirements:**
  - Future space mission to complement COPERNICUS “Sentinels”
    - 2 Hyperspectral sensors (VNIR and SWIR) with 220 spectral bands each.
  - High volume of data => On-board Compression mandatory.
  - Clouds covers more than 50% of the Earth surface.
    - Significant presence of Clouds in CHIME continuous acquisitions.
    - Opaque Clouds are less useful to estimate Earth surface properties.
  - Possibilities to increase on-board data reduction with a selective compression applied on clouds.

---

**Example 1**

European Space Agency.
Thales Alenia Space in Spain.
Thales Alenia Space in France.
IUMA/ULPGC.

- **System requirements:**
  - Performance requirements.
    - Real time: one sample per cycle.
    - 125 MHz of clock frequency.
  - **Xilinx® Radiation Tolerant (RT) Kintex® UltraScale™ QRKU060 FPGA**
On-board Satellite payload data processing

Wide local sums
- Predicts the current sample with a weighted sum of neighbors
- Rice encoding technique. Minimizes the number of bits in a coded block of J samples

Narrow local sums (Favours pipelining)

CCSDS 123.0-B-2
Lossless and Near-lossless Multi/Hyperspectral Compressor

Example 1
On-board Satellite payload data processing

• Solution analysis
  • Solution 1: **DSQ**. Some bits of **pixel-clouds** are set to 0.
  • Solution 2: **DAE**. Different errors for **pixel-clouds** and **pixels-no_clouds**.
  • Solution 3: **RtZ**. Set the residuals of cloud-pixels to ‘0’.

• Best in performance **RtZ** (12% better than DSQ) but introduce outliers.
• Selected: **DAE** (Not the best but it doesn’t create outliers).
• Tested with AVIRIS images.
On-board Satellite payload data processing

• Cloud detection and processing algorithms.

• Selected for implementation in the Demonstrator:
  • Cloud Detection: Support Vector Machine (SVM) approach
    • Cloud mask generation: indicates per each pixel if it is cloud (mask = ‘1’) or not (=‘0’)
  • Cloud Processing
    • Pre-quantization for the pixels detected as cloud to improve posterior compression in less useful areas

![Diagram of cloud detection and processing](image)
On-board Satellite payload data processing

- Image reception up to 2Gbps (16 bit samples processed at 125 MHz clock cycle)
- Cloud detection over selected bands: Cloud mask
- Cloud processing
- CCSDS 123 Compression
- Data formatting: processed image + cloud mask
- Compressed image transmission
- TMTC (Telemetry and Telecommand) module for design configuration
On-board Satellite payload data processing

- Demonstrator TEST Procedure
On-board Satellite payload data processing

HW Description: KCU105 DUT board + UMFT601X-B Test Mezzanine

- UMFT601X-B Mezzanine
  - Manufacturer: FTDI
  - USB 3.0 to FIFO interface bridge
  - 2 parallel FIFOs with up to 32 bits at 66.67 MHz (Max 2.13344Gbps)

- KCU105 board
  - Manufacturer: Xilinx
  - FPGA: Xilinx Kintex Ultrascale, XCKU040-2FFVA1156E
  - External Memory: 16 Gb DDR4
  - Control interface: UART
  - Data Input and output interfaces: FMC connector
  - USB JTAG to program the FPGA
This project has received funding from the European Union’s H2020 research and innovation programme under grant agreement No 870485.
On-board Satellite payload data processing

Video Imaging Device For Earth Observation

• The project aims to develop a highly-disruptive technology for a next-generation instrument offering Video Observation of Earth.

• A novel architecture will be demonstrated, based on state-of-the-art technologies for mirrors (freeform), structures (additive manufacturing) & detection (new generation detector & processing chain).

• It will allow to answer new types of problematics and missions, anticipating the emergence of on-board smart algorithms.

• Partners:
  • Thales Alenia in Space France SAS (coordinator)
  • Thales Alenia in Space Spain
  • University of Las Palmas de Gran Canaria
  • Poly-Shape (now AddUp)
  • Pyxalis
  • AMOS

Gigapyx RGB sensor from Pyxalis is expected to provide a large image in terms of spatial resolution (48Mpixels). 10 FPS for HD video sequences
On-board Satellite payload data processing

• **GOALS OF THE VIDEO CHAIN**
  - Capable of performing high-resolution RGB images and video monitoring on an extremely wide scene.
  - Two modes of operation: detection (image mode) and compression plus tracking (video mode).
    - **Image mode**: detecting objects in the acquired scene.
    - **Video mode**: tracking of the object of interest and smart video compression of the ROI.
  - Flying trajectory and speed known in advance → Motion estimation seems not relevant.
  - Adapt the video compression ratio depending on the satellite available resources and to the available downlink bitrates.
  - Implemented on a Radiation Tolerant FPGA: Xilinx UltraScale XCKU060.
On-board Satellite payload data processing

- Detection: Proposed detection solution
  - Based on convolutional neural networks (CNNs)
  - High detection capabilities
  - A single CNN architecture can be trained for different purposes.
  - The detection performance can be modified by replacing the pre-trained weights without modifying the network architecture.

High Level tools:
Python - Keras, Tensorflow

Training of the CNN:
- Different weights depending on use case.
- NN can be re-trained and weights uploaded via the uplink.


On-board Satellite payload data processing

• Detection: architecture overview
  • 10 different architectures analyzed at Keras.
  • MobileNet-Reduced:
    • Good compromise between accuracy and complexity.
    • Number of filters divided by 4 compared to standard MobileNet.
• Detection strategy:
  • Each video frame will be independently processed as an RGB image by the CNN.
  • Processing the received lines without waiting for the full image.
  • Each image will be processed applying a sliding window with a certain stride and overlap.
  • A window size of 256x256 pixels should give enough margin for target detection.

The window moves from left to right and from top to bottom.

The window moves from left to right and from top to bottom.

Ship detected.

High Performance and Disruptive Computing in Remote Sensing
On-board Satellite payload data processing

**SYSTEM: TEST SET-UP**

- The whole video processing have been validated.
  - A test set-up has been developed on a Xilinx Kintex UltraScale **XCKU040** FPGA.
  - The whole validation set-up also runs at a clock frequency of **200 MHz**, except the DDR4 controller (300 MHz).
- A test dataset comprised by short video sequences where boats are captured at different locations was created.
- Three outputs are generated (one per compression instance) and sent back to the control PC, independently decompressing them with an in-house software compliant with the CCSDS 123.0-B-2 standard.
  - The three decompressed files are merged into a single YCbCr video sequence for visualization purposes.
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Conclusions
High Performance Space Computer

- New Space (NS) is a completely new approach.
  - Smaller satellites.
  - More computation on-board.
  - Shorter earth-to-Space time.
  - Constellations (mainly in Low Earth Orbit).
  - Private funding.
  - One satellite many solutions.

- HPSC: High Performance Space Computing is a hot topic today.
  - Modular systems.
  - Demand computing on-board.
  - Standardization is required.
  - Needs to use the last technological advances (FPGAs, etc).
  - Using COTS for LEO orbits.

- Example 1: CHIME mission.
  - New mission in the Copernicus program.
  - Long life with public information.
  - Reduce information on cloudy scenes.

- Example 2: European VIDEO project.
  - Use a complex approach for Space.
  - Image mode and video mode.
  - CNN for ship detection with possibility to adapt.
Conclusions
Future of HPSC

- AMD-Versal MPSoC
  - Full system on a chip
  - 2xARM Cortex-A72; 2X ARM Cortex-R5F; AI Engine; DSP-Engine; Programmable Logic; NoC; etc. etc.

- RISC-V
  - New standard on Space?
  - Link between HPSC and HPC on ground?
  - Solutions: NOEL-V, Microchip Polarfire, De-RISC, Occamy, etc.

- GPUs
  - Nvidia Jetson Nano, TX1, etc.

- Quantum computing
  - Disruptive computing in this workshop!
Hyperspectral technology: inspiring ideas, challenges and opportunities

Part III: Additional projects

José López-Feliciano/Roberto Sarmiento
Institute for Applied Microelectronics (IUMA)
Outline

• The institute for Applied Microelectronics at ULPGC
• Why hyperspectral technology?
  • Some numbers
  • Applications
• Introduction to hyperspectral technology
  • The human eye
  • Multi- vs hyperspectral sensors
  • Types of hyperspectral sensors
• Ongoing projects
  • Space
  • Precision agriculture
  • Environment
  • Health
Past and on-going projects
Past and on-going projects
Past and on-going projects

1. Cosmódromo de Plesetsk
   1966
   1957-2021: 1589 lanzamientos

2. Cosmódromo de Baikonur
   1957
   1957-2021: 1431 lanzamientos

3. Cabo Cañaveral
   1958
   1957-2021: 935 lanzamientos

4. Base Aérea Vandenberg
   1959
   1957-2021: 625 lanzamientos

5. Puerto Espacial Kourou
   1970
   1957-2021: 296 lanzamientos
Past and on-going projects

Velocity at Earth’s Surface by Latitude

Latitude (°N)*

Velocity at Surface (m/s)

Guiana Space Centre 463 m/s
Cape Canaveral / KSC 408 m/s
Vandenberg 382 m/s
Baikonur 323 m/s
Plesetsk 212 m/s
Past and on-going projects
Past and on-going projects

San Marco Platform (Kenya)
1964-1988
Past and on-going projects

**FUTURE FARMS**
small and smart

**SURVEY DRONES**
Aerial drones survey the fields, mapping weeds, yield and soil variation. This enables precise application of inputs, mapping spread of pernicious weed blackgrass could increasing Wheat yields by 2-5%.

**FLEET OF AGRIBOTS**
A herd of specialised agribots tend to crops, weeding, fertilising and harvesting. Robots capable of microdust application of fertiliser reduce fertiliser cost by 99.9%.

**FARMING DATA**
The farm generates vast quantities of rich and varied data. This is stored in the cloud. Data can be used as digital evidence reducing time spent completing grant applications or carrying out farm inspections saving on average £3,300 per farm per year.

**TEXTING COWS**
Sensors attached to livestock allowing monitoring of animal health and wellbeing. They can send texts to alert farmers when a cow goes into labour or develops infection increasing herd survival and increasing milk yields by 10%.

**SMART TRACTORS**
GPS controlled steering and optimised route planning reduces soil erosion, saving fuel costs by 10%.
Past and on-going projects

World population growth, 1700-2100

- Annual growth rate of the world population

World population

Data sources: Our World in Data based on HYDE, UN, and UN Population Division (2019 Revision)
This is a visualization from OurWorldinData.org, where you find data and research on how the world is changing.

29/06/2023

High Performance and Disruptive Computing in Remote Sensing
Past and on-going projects

However, different crops require different amounts of water.

- To produce 1kg of Potatoes requires 250 liters of water.
- 1400 liters of water for Wheat.
- 2000 liters of water for Soybean.
- 3400 liters of water for Rice.
Past and on-going projects
Past and on-going projects
Past and on-going projects

![Graph showing reflectance vs. wavelength for dry and wet soil.](Image)

- **Dry soil**
- **Wet soil**
Past and on-going projects

\[
\text{Healthy Plant} \quad (.48 - .09) / (.48 + .09) = .68
\]

\[
\text{Stressed Plant} \quad (.39 - .32) / (.39 + .32) = .10
\]

\[
0 \leq \text{NDVI} \leq 1
\]

\[
\text{NDVI} = \frac{\text{NIR} - \text{RED}}{\text{NIR} + \text{RED}}
\]
Past and on-going projects
Past and on-going projects
Past and on-going projects
Past and on-going projects
Past and on-going projects

PRECISION AGRICULTURE

NDVI false color image of a vineyard (taken from a UAV in Gran Canaria)
Past and on-going projects
Past and on-going projects
Past and on-going projects
Past and on-going projects
Past and on-going projects

CURRENT LINES OF STUDY
• Spectral analysis of oil spills
• Unsupervised semantic segmentation NN
• Detection of floating debris at sea
Past and on-going projects

• DEEP WATER HORIZON
  Location: Gulf of Mexico in 2010
  Duration of discharge: 3 months

• NORMALIZED DIFFERENCE OIL INDEX

\[ NDOI = \frac{\lambda_{599} - \lambda_{870}}{\lambda_{599} + \lambda_{870}} \]

• AVIRIS SENSOR
  224 bands in VNIR-SWIR
Past and on-going projects

**ENVIRONMENT**

### Most Cited Indices for Identifying Spills

<table>
<thead>
<tr>
<th>Index</th>
<th>Equation</th>
<th>Measured property</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAI</td>
<td>((\text{Blue} - \text{IR}) / (\text{Blue} + \text{IR}) \sqrt{\sum_{i=1}^{N} b_i^2})</td>
<td>Oil fluorescent characteristics</td>
</tr>
<tr>
<td>FI</td>
<td>((\text{Blue} - \text{Red}) / (\text{Blue} + \text{Red}))</td>
<td>Oil fluorescent characteristics</td>
</tr>
<tr>
<td>OSI</td>
<td>(\frac{DN_{\lambda_{\text{Red}}} - DN_{\lambda_{\text{Yellow}}}}{(\lambda_{\text{Red}} - \lambda_{\text{Yellow}})})</td>
<td>Existence of crude oil</td>
</tr>
<tr>
<td>CDOM</td>
<td>(\frac{R_{565}}{R_{660}})</td>
<td>Seawater characteristics</td>
</tr>
<tr>
<td>CHL</td>
<td>(\log(\max(R_{433,490,510})/R_{555}))</td>
<td>Surface chlorophyll (a)</td>
</tr>
<tr>
<td>NDVI</td>
<td>((\text{NIR} - \text{Red}) / (\text{NIR} + \text{Red}))</td>
<td>Live green vegetation</td>
</tr>
</tbody>
</table>

![Images of indices](image-url)
Past and on-going projects
Past and on-going projects

ENVIRONMENT

MTOW 4000 kg
PAYLOAD 1850 kg
ENDURANCE 25 hours
AUTONOMOUS AMPHIBIOUS REMOTELY PILOTED
Past and on-going projects

The main goal of the HELICoiD project is to apply hyperspectral imaging techniques to the precise localization of malignant tumours during surgical procedures. The HELICoiD project will develop an experimental investiga- tory setup based on non-invasive hyperspectral camera. This will be connected to a platform serving a set of algorithms which are capable of discriminating between healthy and pathological tissues. The prototype will be developed with the aim of recognizing cancer tissues during the surgical procedure in real time. This information will be provided to the surgeon via different display devices, and in particular by overlaying the conventional images with a virtualized color map to indicate the proba- bility of any currently assessed tissue being cancerous. To meet these real time and in vivo cancer detection requirements, a hardware/software pack- age that this platform will be derived, which will exist on the computa- tional level requirements of the algorithms which are developed.

The integration of hyperspectral imaging and intraoperative image- guided surgery systems should have a direct impact on patient outcomes. Potential benefits include allowing confirmation of complete removal during the surgical procedure, avoiding complications due to “totoe tissue”, and providing confidence that the goals of the surgery have been achieved.

A multidisciplinary consortium composed of surgeons, pathologists, IT engineers, mathematicians and physicists has been created. Two European hospitals will be involved as end-users, in testing the require- ments for, and conducting validation of, the tools and systems developed within the project. If hyperspectral imaging techniques are demonstrated to be practical for surgical applications then it is expected that Europe- wide medical industry related to hyperspectral imaging will be well poised to exploit this opportunity for growth.

The best prospects for success in this project rest with the algorithms and software implementations co-exploration paradigm. It is our belief that translation of hyperspectral imaging technology to real-world medical applications will be achieved by developing algo- rithms, architectures and implementations separately. Rather, this goal is better served by adopting a fully integrated approach from the outset.

Health

HEALTH

Brain cancer is one of the most important forms of the disease, and is a significant economic and social burden across Europe. The most common form is high-grade malignant gliomas, which account for approximately 33–35% of primary brain tumours, with multifocal glioblastomas making up 45% of these cases. These types of gliomas are characterized by fast- growing invasiveness, which is locally very aggressive, are in most cases unscreenable and are rarely amenable to surgical removal.

Despite the introduction of new aggressive treatments combining surgery, radiation therapy and chemotherapy, their continues to be treatment failures in the form of partial or locally recurrent tumours (i.e. recurrence at the primary tumour location or within 2.5 cm of adjacent tissue). Median survi- val periods and 5-year survival rates for pilocytic astrocytoma are only 35 months and 19%, respectively; whereas for glioblastoma multiforme these are 10 months and less than 5%, respectively.

The relevance and importance of complete resection for low grade tumours is well known, especially in paediatric cases. However, traditional diagnoses of internal tumours are based on sectional biopsy followed by histology or cytology. The main weakness of this standard methodology is well known. Firstly, it is an aggressive and invasive diagnosis with potential side effects and complications due to the surgical excision of both malignant and healthy tissues, and secondly diagnostic information is not available in real time and requires that the tissues are processed in a laboratory.

There are several alternatives to conventional optical visualization through a surgical microscope, including magnetic resonance imaging (MRI), computed tomography (CT) ultrasonography. Despite warming and nuclear medicine. Unlike these approaches, hyperspectral imaging offers the prospect of precise detection of the edges of the malignant tissues in real time during the surgical procedure.
Past and on-going projects
Past and on-going projects