CONTRIBUTION OF A POWERFUL IMAGE PROCESSING UNIT TO THE AUTONOMY OF ROBOTIC INSTRUMENTS

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Rationale

A first analysis of current and future science space missions has highlighted the strategic needs of a miniaturised Imaging Processing Unit (IPU) able to perform image processing using complex algorithms, together with being compliant to low power, harsh environment and extended temperature range constraints.

The figure illustrates the IPU within a mechanical box:

a highly effective miniaturised processing unit operating under harsh conditions.
IPU (Imaging Processing Unit) description

Typical applications for the IPU

- **Image processing**
  - Image compression
  - Distortion correction
  - On-board calibration
  - Integration time optimization
  - Image registration
  - Stereo reconstruction
  - Depth of field extension
  - High dynamic range imaging
  - Super-resolution
  - Image analysis

- **Support to navigation**

- **Co-processor to the OBC**

- **Monitoring**
IPU (Imaging Processing Unit) description

IPU global architecture

- Sensor 1
- Sensor 2
- Sensor n
- Sensor n-1
- 100 Mbps link 1
- 100 Mbps link 2
- 100 Mbps link to host(s)
- Power supply I/F
- Power management part
- Data I/F part
- Data processing part
IPU (Imaging Processing Unit) description

Data processing unit components

- A communication FPGA
- A data processing FPGA
- A “system on chip” (SOC) processor embedded in the data processing FPGA
- A mass data storage memory
- A processor code memory
IPU (Imaging Processing Unit) description

Data processing FPGA internal architecture

- Meaner
- Polynomial multiplication
- Filter
- Interpolator
- Geometric functions
- RLE
- Quantization
- Application-Specific Logic
- Pixel selector
- Memory controller
- Processor Core
- FPU
- D-Cache, I-Cache
- Timers
- External ram for image storage
- External flash for processor instructions
- System bus
- FPGA
Advantages of the philosophy

- Speed improvement
  - Parallelization of the operations
  - Every processing parts inside the FPGA

- Good versatility
  - Tuneable FPGA design
  - Anytime reprogrammable processor code

- Immunity to radiations
  - Anti-fuse FPGA technology
  - Radiation tolerant components
  - Robust firmware functionalities to detect and correct (SEU) errors

- Low mass and power
  - Low number of components
  - Limited clock frequency
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Data processing unit specifications

Preliminary requirements

- Immunity to radiations (level depends on the mission)
- Low power (max 2.5W)
- Miniaturisation (smallest packages, component number minimization)
- High data rate links to sensors and host spacecraft
- Embeds a mass storage memory
- Embeds high efficiency data processing algorithms
- Re-programmable capability.
### Data processing unit specifications

#### Presented unit specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Radiation and fault tolerance.</strong></td>
<td>• Variant 1: 100 krad 300 krad</td>
</tr>
<tr>
<td><strong>Two possible variants:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Sensors data links:</strong></td>
<td>• Number of links: 2 physical (numerous addressable peripherals)</td>
</tr>
<tr>
<td></td>
<td>• Links type: SpaceWire</td>
</tr>
<tr>
<td></td>
<td>• Links speed: 100 Mbits/s</td>
</tr>
<tr>
<td><strong>Interface with host spacecraft:</strong></td>
<td>• Link type: SpaceWire</td>
</tr>
<tr>
<td></td>
<td>• Link speed: 100 Mbits/s</td>
</tr>
<tr>
<td><strong>Storage memory:</strong></td>
<td>• Memory type: SRAM</td>
</tr>
<tr>
<td></td>
<td>• Memory size: 512 Mbits</td>
</tr>
<tr>
<td><strong>Processor code memory:</strong></td>
<td>• Memory type: EEPROM</td>
</tr>
<tr>
<td></td>
<td>• Memory size: 1 Mbits</td>
</tr>
<tr>
<td><strong>Global clock frequency (min – max)</strong></td>
<td>50MHz - 100MHz</td>
</tr>
<tr>
<td><strong>Data processing FPGA:</strong></td>
<td>• Technology: Anti-fuse</td>
</tr>
<tr>
<td></td>
<td>• Capacity: ~60k cells</td>
</tr>
<tr>
<td><strong>Communication FPGA:</strong></td>
<td>• Technology: Anti-fuse</td>
</tr>
<tr>
<td></td>
<td>• Capacity: ~20k cells</td>
</tr>
<tr>
<td><strong>Power supply:</strong></td>
<td>• Voltage: +5V</td>
</tr>
<tr>
<td></td>
<td>• Power consumption: &lt; 2.5W</td>
</tr>
</tbody>
</table>
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Potential applications in support to the robotic instruments’ autonomy

Non-exhaustive list of well suited applications for the IPU

- Path planning
  - Image registration
  - Stereo reconstruction
  - Features detection
- Positioning, rendezvous
  - Management of data coming from several positioning sensors
  - Target recognition from images
- Image analysis (e.g. features detection)
  - Dynamic range enhancement (HDR)
  - Depth of field extension
  - Sharpness measurement
  - Exposition measurement
- Sensors data processing
  - Signal filtering
  - Relevant values extraction
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Application example & performances

Typical application selection

- Image processing on pictures from two sensors of 2048x2048/16bits pixels with the following algorithms:
  - Image compression: high efficiency wavelet based lossy and lossless algorithm
  - Distortion correction: radial distortion correction standard algorithm
  - Dark calibration: dark signal and non-uniformity measurement
  - Integration time optimization: measurement of the exposure and correction of the integration time
Application example & performances

Data processing FPGA logical blocks

- Pixel selection
- Meaning
- Polynomial multiplication
- Filtering
- Interpolation
- Run length encoding
- Quantization
- Geometric functions
Application example & performances

Data processing FPGA space repartition

- Meaner: 6%
- Polynomial multiplicat.: 5%
- Interpolator: 5%
- Filter: 6%
- Geometric functions: 2%
- Run length encoding: 1%
- Quantizat.: 1%
- Pixel selector: 2%
- SOC processor: 13%
- Main control: 23%
- Free space: 36%
# Application example & performances

## Algorithms efficiency

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Operations number</th>
<th>Clk cycles number</th>
<th>Efficiency @ 50MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression</td>
<td>397 MOP</td>
<td>28 M</td>
<td>700 MOPS</td>
</tr>
<tr>
<td>Distortion correction</td>
<td>71 MOP</td>
<td>21 M</td>
<td>170 MOPS</td>
</tr>
<tr>
<td>Integr. Time optimization</td>
<td>14 MOP</td>
<td>4 M</td>
<td>175 MOPS</td>
</tr>
<tr>
<td>Dark calibration</td>
<td>69 MOP</td>
<td>69 M</td>
<td>50 MOPS</td>
</tr>
</tbody>
</table>

MOP: Mega operations  
MOPS: Mega operations per second  
Efficiency is calculated by dividing the operations number by the number of clock cycles needed and multiplying the result by the clock frequency
Application example & performances

Reached performances

- **Storage capabilities:**
  Store 8 pictures of 2048x2048 with 16 bits pixels

- **Processing capabilities @ 50MHz:**
  Process images from two cameras (2048x2048 16bits) at 1Hz frequency, with the following algorithms:
  - High efficiency lossy or lossless compression (wavelet based)
  - Distortion correction
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IPU application development

- **Hardware:**
  - Two radiations immunity specifications available
  - Not modifiable

- **Firmware (FPGA VHDL code):**
  - Programmed once on Earth, not upgradable
  - Tuneable according to the mission (logical blocks)

- **Software (SOC processor code):**
  - Can be updated any time during the mission
  - Uses FPGA logical blocks as functions
Use of the IPU for space missions

Typical application selection

**VHDL logical Block library**
- PID controller
- Crop
- Meaner
- Polynomial multipl.
- Filter
- Interpolator
- Geometric funct.
- RLE
- Quantization
- Pixel selector
- Integrator
- ...

**Data processing FPGA**
- Processor code memory
- Distortion correction
- Compression
- ...
- SOC processor
- Application-Specific Logic
  - Polynomial multipl.
  - Filter
  - Interpolator
  - Geometric funct.
  - Quantization
  - Pixel selector
Conclusion

The IPU is:

- A powerful support to the spacecraft electronics for specific low level applications
- Compliant with low mass and low power requirements
- Able to process a large amount of data in a short time, thanks to its parallel computation capability
- Compliant with harsh space environment (radiations, temperature)
- Capable of bringing a valuable support to the OBC
- Versatile. Its VHDL code is tuneable to suit the mission. Its software is upgradable anytime
- A substantial contributor to the autonomy of robotic space instruments, allowing an important reduction of data to be processed on Earth
Thanks for your attention

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