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1 Relevant Background and Reference Documents

2 Acronyms

AI Artificial Intelligence
API Application Programming Interface

BSP Board Support Package

CBR Constant Bit Rate
COTS Commercial Off The Shelf

DRAM Dynamic Random Access Memory

eMMC embedded Multi-Media Card
ESA European Space Agency

FDIR Fault Detection, Identification and Recovery
FPS Frames Per Second

HTTP Hypertext Transfer Protocol

ISC Intelligent Space Camera
ISP Image Signal Processor

JSON JavaScript Object Notation

LED Light Emitting Diode

MIPI Mobile Industry Processor Interface

NN Neural Network
NTP Network Time Protocol

REST Representational State Transfer
RTSP Real Time Streaming Protocol

SEI Supplemental Enhancement Information
SEL Single Event Latch-up

VMC Visual Monitoring Camera
VPU Vision Processing Unit

3 Introduction

This document summarises the Intelligent Space Camera (ISC) prototype solution. It is an Artificial Intelligence (AI) enabled camera in a compact and self-contained form factor for space applications, for which data and control are transported over an Ethernet interface. The solution has been developed by Ubotica as part of an European Space Agency (ESA) GSTP de-risk project. ESA is currently promoting the development of AI-based solutions for space applications, and Commercial Off The Shelf (COTS)-based glsAI processing on-satellite has already successfully been demonstrated by ESA in previous missions that enable these new capabilities.

The ISC device has been designed from the ground up with space applications in mind. The use of a radiation-characterised COTS processor (with additional tests scheduled), full on-board latch-up functionality, external control and warning signals, all integrated into a small form factor, ensure a robust and failure-resistant device capable of bringing advanced image-based artificial intelligence onto satellite.

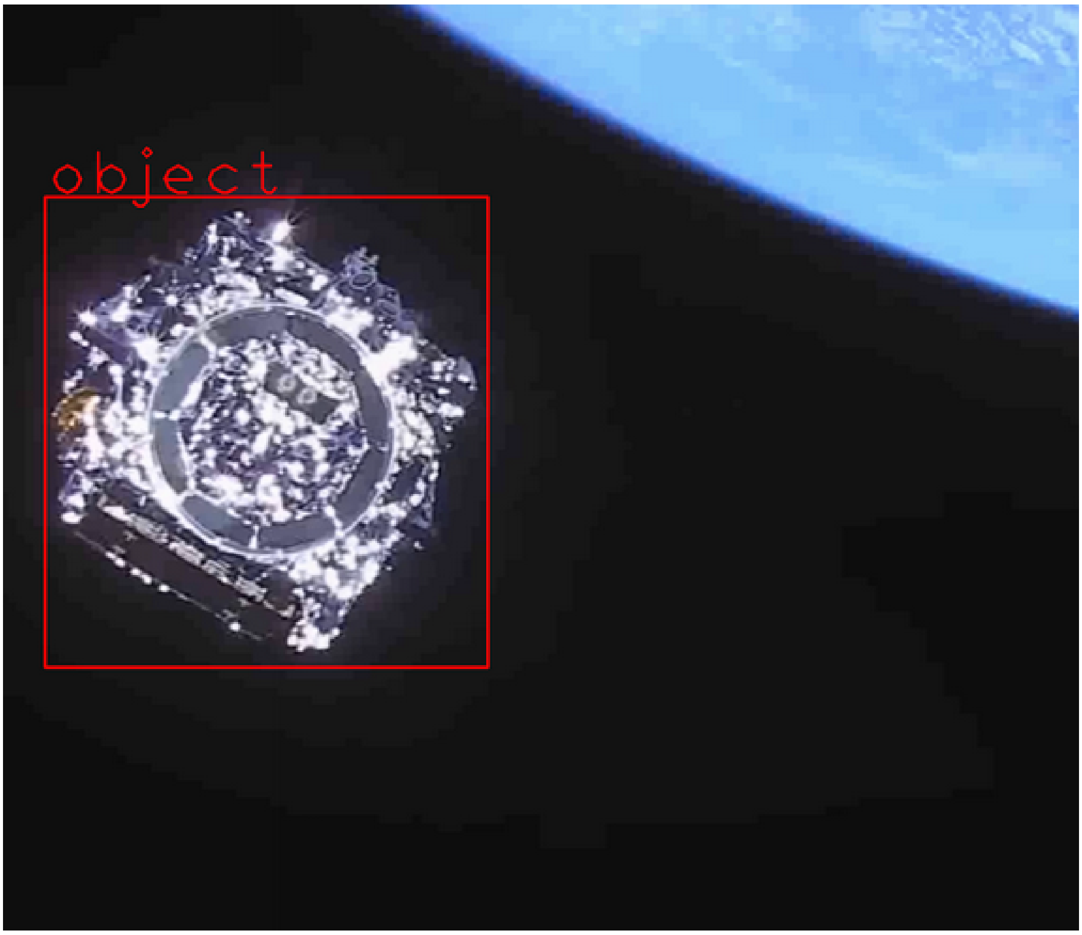

Figure 1: Sample ISC demonstrator output for on-camera object tracking

The ISC is capable of streaming compressed video in H.265 (HEVC) at a maximum resolution of 4K and 60 Frames Per Second (FPS) (equivalent configurations such as FHD/120 FPS are also supported). It is configured remotely via a RESTful Application Programming Interface (API) that exposes a series of endpoints that allow information and control commands to be exchanged with the camera. In this way the host can dynamically (re)configure the device, and receive status information, video frames and inference results at frame rate.

The camera's intelligence is in the system's ability to perform inference operations using different kinds of Neural Networks (NNs), allowing to take decisions in real time, as well as to include the results in the video stream itself, either as metadata or as an overlay on the frames. NNs can be easily ported to this new platform using the freely available OpenVINO tools. Models from all common frameworks (Caffe, TensorFlow, PyTorch, ONNX) are supported. In addition, both the hardware and software of the system have been designed to be compatible with Ubotica's CogniSAT™ solution framework.

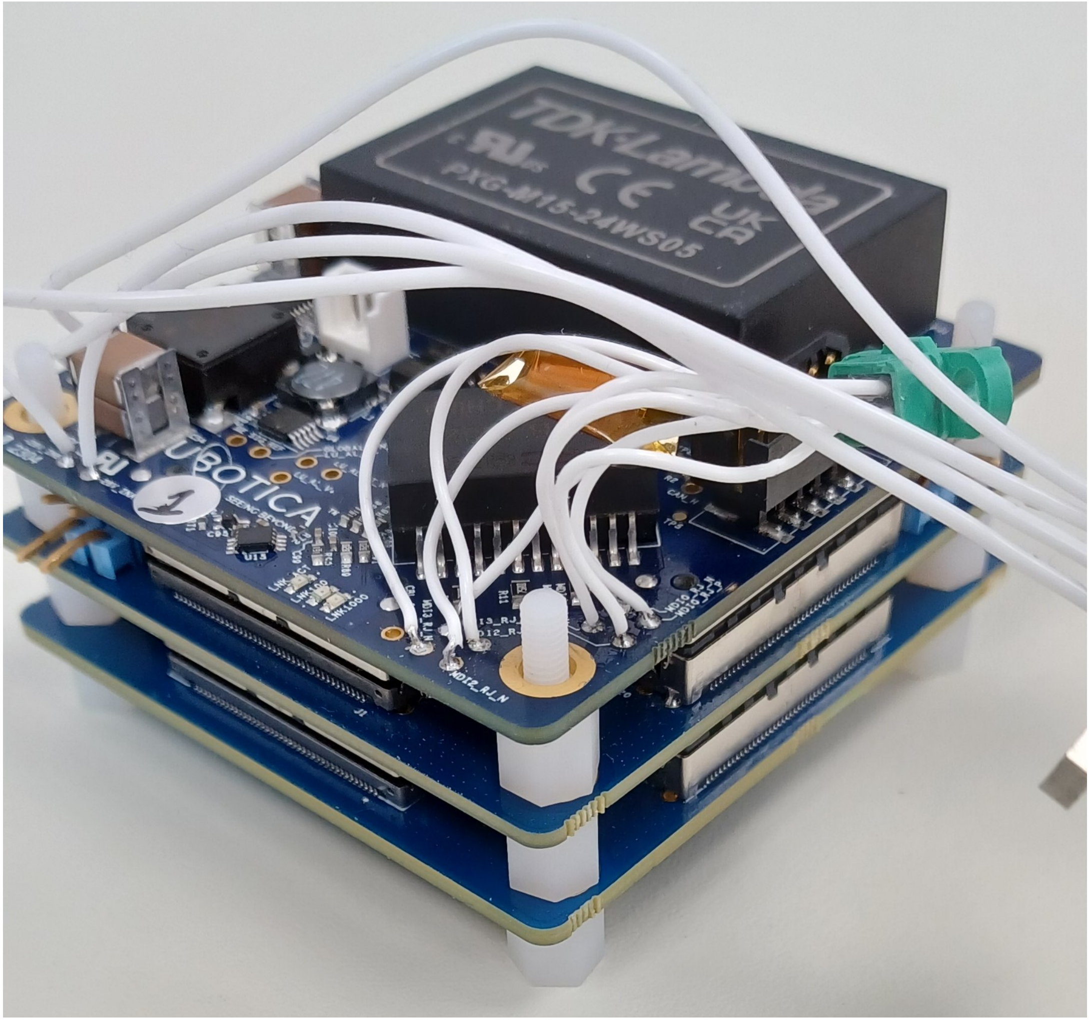

Figure 2: ISC board stack

The NNs blob is loaded to the camera prior to operation, but in the future it will be possible to transmit it to the camera by the same mechanism as the configuration, using the RESTful API. Once it is received, the camera is reconfigured to perform inference of the frames as they are received from the camera sensor. The way this information is sent varies depending on the type of NN used, for example, if the result of the read is a (or several) bounding box(es) this information can be included as an overlay in the frame itself.

The main purpose of the ISC is to serve as a platform to enable satellite visual monitoring applications in their broadest sense - it is a Visual Monitoring Camera (VMC). In particular,

the ability to apply a full Image Signal Processor (ISP) pipeline in hardware at frame rate, in combination with a tightly integrated and hardware-accelerated AI engine directly operating on the
glsISP output, gives the camera the capability to stream output to a downstream consumer in an actionable-ready format. An example of this is fiducial marker tracking for rendezvous scenarios, where, instead of loading the host processor with full-frame data that has to be processed further, the ISC directly extracts the marker locations and sends only this pertinent information, freeing up host processing for the rendezvous control loop. In another deployment example, the ISC can be configured as a smart sensor for visual Fault Detection, Identification and Recovery (FDIR), wherein it 'silently' performs AI-driven solar panel inspection - only notifying the host when a change occurs or when aberrant features are detected in the frame.

4 Hardware architecture

The design of the ISC device consists of three different boards built using COTS parts, with the 3-board stack enabling a compact form factor with a total bounding size of approximately 70x60x40mm. Figure 2 shows the final camera board stack. The three boards have logical functional grouping as follows:

- **Bottom board - Europa**: Contains the Myriad X Vision Processing Unit (VPU) for all on-board processing, the primary sensor interface, system Dynamic Random Access Memory (DRAM), flash memory and embedded Multi-Media Card (eMMC) memory.
- **Middle board - Callisto**: Encompasses all power management components and the latch-up protection circuitry. Per-rail current monitoring improves the ISC's resilience to cosmic radiation in the space environment by removing power on detection of current spikes indicative of Single Event Latch-ups (SELs). Current monitors are software-configured to trigger when the current exceeds a threshold.
- **Top board - Io**: Contains the system external interfaces, along with the front-end power conditioning and step-down, and a Light Emitting Diode (LED) flash driver.

The sensor and optics are decoupled from the ISC design in order to enable flexibility for a range of deployments and applications: the ISC supports any 2-lane or 4-lane Mobile Industry Processor Interface (MIPI) sensor. For development and demonstration purposes, a custom Full-HD global shutter sensor board has been designed for use with the camera.

5 Software architecture

The software implementation consists of a firmware application running on the Myriad X processor (which has proven capability to run NNs in space), along with a RESTful API specification for host control. As part of the firmware development within the ISC project, hardware drivers, a Board Support Package (BSP), and multiple high-level components for atomic processing functions have been developed. Figure 4 shows how the different components of the firmware application are mapped onto different execution blocks within the Myriad X.

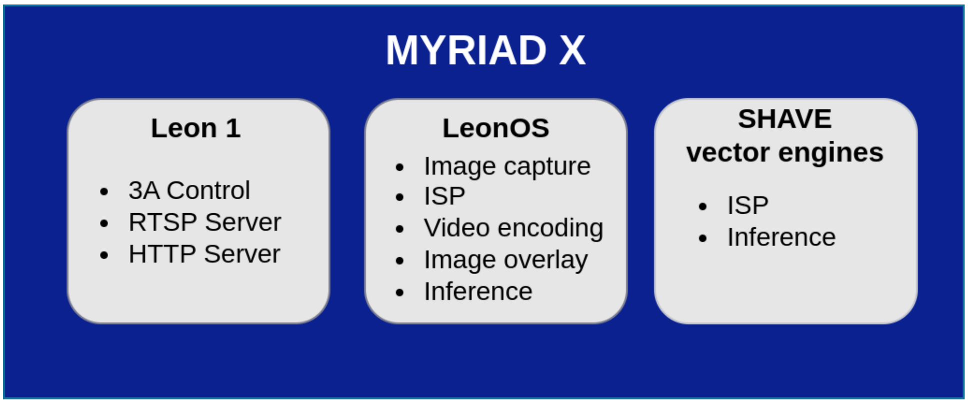

Figure 3: ISC functional blocks mapped to their corresponding execution processing executors on Myriad X

The application architecture is based on a loosely coupled pipeline architecture consisting of software plugins with integrated flow-control. These simplify the development of complex image processing applications by wrapping operations in a standard plugin-based interface. Plugins can then be connected to other plugins in a directed graph structure referred to as a pipeline. All the modules that are described below can be related with one or more of these plugins. Figure 4 shows the ISC high-level plugin architecture, with the corresponding inputs and outputs from the system. The *NN inference* plugin is the NN acceleration engine that provides the in-line AI processing capabilities.

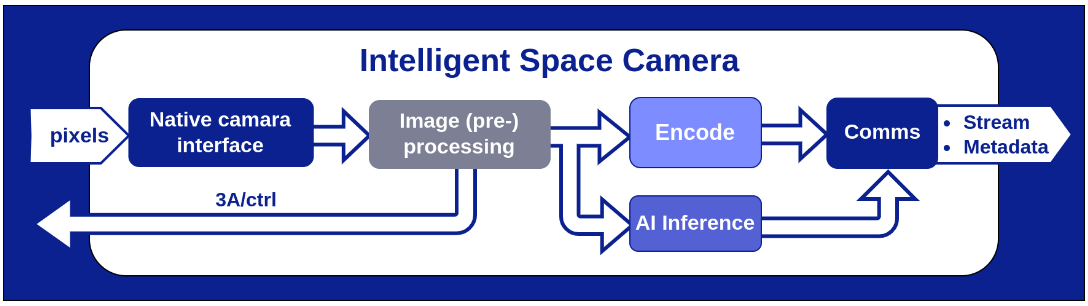

Figure 4: ISC high-level software architecture

Towards the top of the image is shown the raw frame inputs being acquired directly from the camera. These are processed through the ISP plugins hardblocks. In this way, two frames are produced, the "full frame", which is the one that is passed to the H.265 hardblock plugin and transmitted by Real Time Streaming Protocol (RTSP) streaming, and the "resized frame", which is used as input for the inference with the selected NN. The result of the inference is included as metadata (Supplemental Enhancement Information (SEI) in particular) in the RTSP stream. It is also possible to directly include the inference result in the "full frame" as an overlay on the image. This can be especially useful in the case of object detection in live-streaming applications, such as for on-board launch and payload dispensing monitoring, where it eliminates the need to post-process the received stream prior to display, thus reducing latency.

5.1 Device capabilities

Some of the key features of the ISC, in addition to the AI inference capability, are described below:

- **Time synchronisation**: Two forms of time synchronization are planned for the ISC: Network Time Protocol (NTP) (implemented) and IEEE1588 PTPv2 (pending - phase 2), with the latter targeting applications where the highest level of time precision is required. In addition to supporting synchronized frame capture, all the captured frames include the time stamp of the instant of capture in the form of an image overlay.

- **Image overlay**: Before the H.265 encoding step, the frames are passed through the custom image overlay plugin. This allows text and/or logos to be added anywhere on the frame, at the framerate. This plugin can be also used to draw bounding boxes (e.g., from NN inference results) onto the frame itself.

- **RESTful API**: A Representational State Transfer (REST) API is used as the user interface to the application from the host side, providing a standard way to communicate with the application over Hypertext Transfer Protocol (HTTP). REST involves using standard HTTP methods (such as GET and POST) to interact with the application in a structured yet flexible way. The data itself is represented using the extensible JavaScript Object Notation (JSON) format. Several endpoints are exposed, including ones for configuration setting and for health status monitoring.

- **H.265 video compression**: H.265 video encoding is available entirely in hardware on the ISC, and can be configured via the RESTful API. Among the supported compression configurations is that of Constant Bit Rate (CBR), which enables the encoder to produce a constant bitrate output regardless of other parameters such as resolution or frame rate. This is useful to adjust the bitrate produced by the RTSP stream to the (possibly dynamic) physical conditions at the time (e.g.,, maximizing the use of available bandwidth). Limiting the bitrate to a certain resolution will produce a stream of low visual quality.

- **3A Control**: The ISC implements a full ISP including auto focus, auto exposure and auto white balancing algorithms. These are driven by a Dynamic Tuning Parameter (DTP) file that is pre-calibrated per sensor. The auto focus reset can be triggered using the RESTful API, with auto exposure and auto white balancing algorithms enabled by default.

Additional features, addressing increased remote system reconfigurability, on device recording and results storage and buffering functionality, and AI-driven white balance control, are pending implementation in a follow-on project.

6 Project Achievements

Within the GSTP De-Risk project, a complete prototype design of the ISC was developed, based significantly on requirements established during the early phases of the project. The 3-board design was manufactured, assembled and tested for conformance. A batch of bringup tests were developed and deployed in order to assess the range of intended camera functionalities. Due to difficulties encountered by the assembly house (partially caused by the design being very area-constrained), several the the camera stack were not fully functional. However, a fully functional stack was used to complete bringup. Firmware development enabled the software functionalities of the camera, again developed against the original requirements. Two software features remain outstanding in the primary firmware (sensor stream acquisition and continuous in-line inferencing), but these functions have been verified separately on the ISC hardware using dedicated standalone applications.

A demonstrator that performs training-less AI-based tracking has been developed and ported to representative Myriad X hardware. In a follow-on project it is intended to develop this demonstrator code base further so as to use it to drive a 3A control algorithm on the ISC.

7 Conclusion

This summary document presents the development of an ISC solution, and documents a subset of the features and capabilities of this smart device. It combines image capture, image processing, and image compression capabilities with in-line AI inference functionality, to enable the development of applications that process and extract insights from visual data directly at source and in real-time. In this way the ISC can reduce or eliminate the need for image post-processing on the host, and reduce latency of information delivery to the user whilst providing this information in a format that is aligned with the requirement of the overall application. One of the main uses case for this product is as a VMC, but it can be use to address more problems or application such as visual FDIR, docking and rendezvous verification, and space situational awareness.

