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The Intelligent Space Camera on the "Call to Adventure" SmallSat Mission

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ABSTRACT

In March 2024, the first Intelligent Space Camera (ISC) from Ubotica Technologies was launched on the Apex "Call to Adventure" small satellite mission. The ISC is a designed-for-space camera payload with hardware acceleration of Artificial Intelligence (AI) and Computer Vision (CV) algorithms integrated directly into the camera. Deployable as a self-contained unit within a spacecraft, the ISC manages and executes various processes autonomously and internally without external dependencies, enabling new AI-driven automation-based paradigms and capabilities for space systems. This short paper describes the novel payload, its capabilities, and the mission it is flying on.

INTRODUCTION

While vision systems are becoming more commonplace in both terrestrial and space systems, integration of these systems in any space system is challenging due to power, volume, mass, and reliability constraints. In addition, the interpretation of captured visual data can only be performed algorithmically or by a human on ground, or on limited on-board compute resources. Ubotica has developed the Intelligent Space Camera (ISC) to address this challenge by bringing vision compute and AI capabilities directly on-camera in a low SWaP package. The ISC, alternatively called the CogniSAT-NEI (Non-Earth Imager), operates on the "photons in - insights out" principle. Since raw data is interpreted on imager, centralized compute requirements are minimized by pushing compute out to the data source (sensor), opening up a myriad of use cases. Furthermore, distributed compute architectures that offload visual data interpretation to the camera unit itself can provide both efficiency and redundancy benefits.

The capabilities of the ISC - to process captured frames in-line using AI and CV hardware-accelerated algorithms - allow the camera to directly stream insights extracted from image frames, rather than simply streaming the frames themselves. Pushing the (processing) to the camera itself relieves the satellite's payload processor from having to continuously service and distill frame streams. This system architecture enables numerous use cases for autonomous space systems, including scouting for Earth Observation (EO) systems, relative visual navigation, Space Situational Awareness (SSA), visual Failure Detection, Isolation and Recovery (FDIR), and Rendezvous and Proximity Operations (RPO).

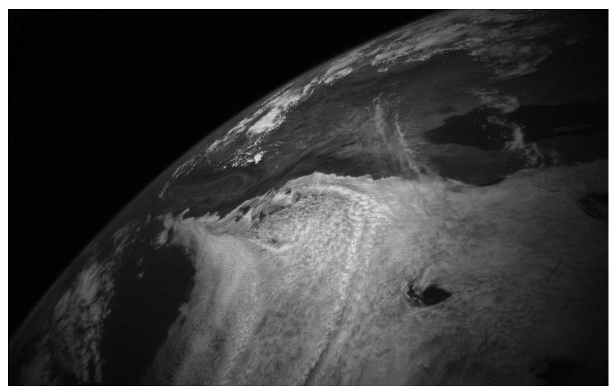

Figure 1: First frame captured by the ISC on the "Call to Adventure" mission.

The "Call to Adventure" mission will demonstrate the ISC's suitability in addressing some of these use cases by proving the camera and processing capabilities in-orbit and verifying the system for use in the space environment. A typical operational sequence during these in-orbit experiments will involve commanding the spacecraft to point to a specified target; capturing a batch of frames on the ISC; performing pre-processing and accelerated AI inference on these frames to extract insights; and storing the insight outputs for subsequent downlink. An example of a captured frame is shown in Figure 1. This paper covers the ISC architecture and its applicability to autonomous space systems, and the potential impact of those use cases on the future of small spacecraft. It additionally details the mission and the system architecture for the first flight of the ISC on the "Call to Adventure" smallsat mission.

INTELLIGENT SPACE CAMERA OVERVIEW

The ISC 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[1]. The ISC is shown in Figure 2. The ISC comprises an optical stack within a ruggedised mechanical enclosure that houses a compact processing and control unit. All on-camera processing is performed by an Intel Movidius Myriad X Vision Processing Unit[2], which enables hardware-accelerated ISP, AI inference, and compression to be applied on-camera at framerate to the high-definition frame stream from the integrated global shutter CMOS sensor. The Myriad X, and its predecessor the Myriad 2, have been validated for space applications in previous work, and have repeated successful spaceflight heritage[3,4]. The ISC's compact form factor allows it to fit within less than 0.5U, making it ideally suited to deployment on small satellites. Designed with automotive-grade Commercial-Off-The-Shelf (COTS) components, its features include an Ethernet interface for command/control and data, a 28V bus step-down powertrain with onboard latch-up protection, non-volatile storage, and signaling peripherals.

Figure 2: The Intelligent Space Camera (ISC)

Within the camera enclosure, the electronics consist of a multi-board stack that enables the best use of available housing volume without restricting functionality. The sensor and optical stack are decoupled from the primary ISC design to enable flexibility for a range of deployments and applications: the ISC supports any 2-lane or 4-lane MIPI (Mobile Industry Processor Interface) sensor. Concerning its external connectivity provisions, the system is equipped with Gigabit Ethernet (GbE) for command/data, with an additional Controller Area Network (CAN) interface for Housekeeping and Telemetry (HKTM).

Camera firmware supports sensor 3A control and a fully hardware configurable Image Signal Processing (ISP) pipeline that processes the Full HD frames at up to 120 Frames Per Second (FPS). Dedicated hardware accelerators for Neural Network (NN) computations on Myriad X provide 1 TOPS of compute, and these are supported by the 16 integrated SHAVE vector engines to enable custom layer processing to support a broad range of NN architectures that are targeted at device via the OpenVINO[10] toolchain. NNs can be uplinked to the ISC at runtime, with an extensive range of AI and camera functionality configurable dynamically via JavaScript Object Notation (JSON) configuration files communicated over HTTP.

Usage Scenarios

One example of a target use case for the ISC is the task of on-satellite debris detection[5]. In this use case, sunlight reflections of objects in Earth orbit are visible as blobs in the image. On-camera processing using AI can recognise these objects in real-time at scale, and without loading the central compute on the satellite's On-Board Computer (OBC). Multiple imagers can be placed at perpendicular orientations in one spacecraft, providing multi-view measurements and redundancy at low SWaP requirements. The output from these individual subsystems could be simple x and y pixel coordinates stored in an onboard database, instead of high-volume image frames that require subsequent processing centrally.

In a second example, the ISC can be used for relative navigation purposes, performing visual navigation pipelines on camera. An example pipeline could be object detection followed by keypoint regression, pose estimation, and even navigation filters, all in sequence, or a subset of this pipeline executed on sensor[6]. In previous work, elements of this pipeline have been verified on the Myriad X processor[7].

Thirdly, the ISC is applicable in EO systems as a scouting subsystem. In this use case, the camera boresight is oriented forward along the spacecraft flight path and is configured such that it has a wider swath than the main EO imager. The camera runs inference on the captured ground track before the nadir facing main EO imager captures the intended Region of Interest (RoI). This allows the spacecraft to autonomously act on the dynamic situation at the RoI, e.g., by canceling an acquisition if the RoI is cloudy or by adjusting the roll angle to capture specific phenomena of interest that would otherwise not have been captured by the narrow main instrument swath. Dynamic targeting can significantly improve the value return of an EO system[8].

Other use cases include deep learning-based star sensor tracking applications[9], vision-based automated failure detection, etc. All of the listed use cases are feasible even in small space systems due to the integrated hardware acceleration in the ISC. Without this efficient and distributed compute architecture, data transfer and centralized compute requirements would make these applications significantly less efficient or even infeasible.

Mission and System Overview

The first flight of the ISC commenced on March 4th, 2024 when the "Call to Adventure" mission was launched on Transporter 10. This spacecraft, built by Apex Space, is a 100 kg dry mass small satellite and carries several payloads in a rideshare configuration.

The Concept of Operations (CONOPS) for the mission is iterative by design. Initially, simple acquisitions at pre-configured times and with set attitude configurations are planned. In addition, periodic memory checks are planned to verify the integrity of the on-camera memory system over time. A number of on-imager image processing experiments are planned to be deployed over the months following payload commissioning.

Since the software of the ISC is configurable and updateable in flight, additional capabilities are planned to be tested over the duration of the mission.

An overview of the system architecture is shown in Figure 3. The system consists of a co-processor and the ISC itself, interfacing over ethernet. This coprocessor is not described here. The ISC is flexible in its application and most payload processors and On-Board Computers (OBCs) can be used as the co-processor. In the current mission, the software architecture consists of a manager residing in the co-processor and controlling system functionalities. For ISC operations, this manager calls different lightweight compiled applications.

Figure 4 shows the high-level functional flow of the manager. The diagram shows two different paths, a frame capture path, and an inference path. These separate paths reflect the initial system operations on the spacecraft, and integrated operations combining both image capture and inference in one functional flow are planned. Due to the modular design of the ISC manager, the integration of both functional flows into one processing pipeline is straightforward. The manager can be configured through a JSON configuration file, which allows the specification of operational parameters and customisation of the manager's behavior without requiring any re-compilation or firmware/software updates.

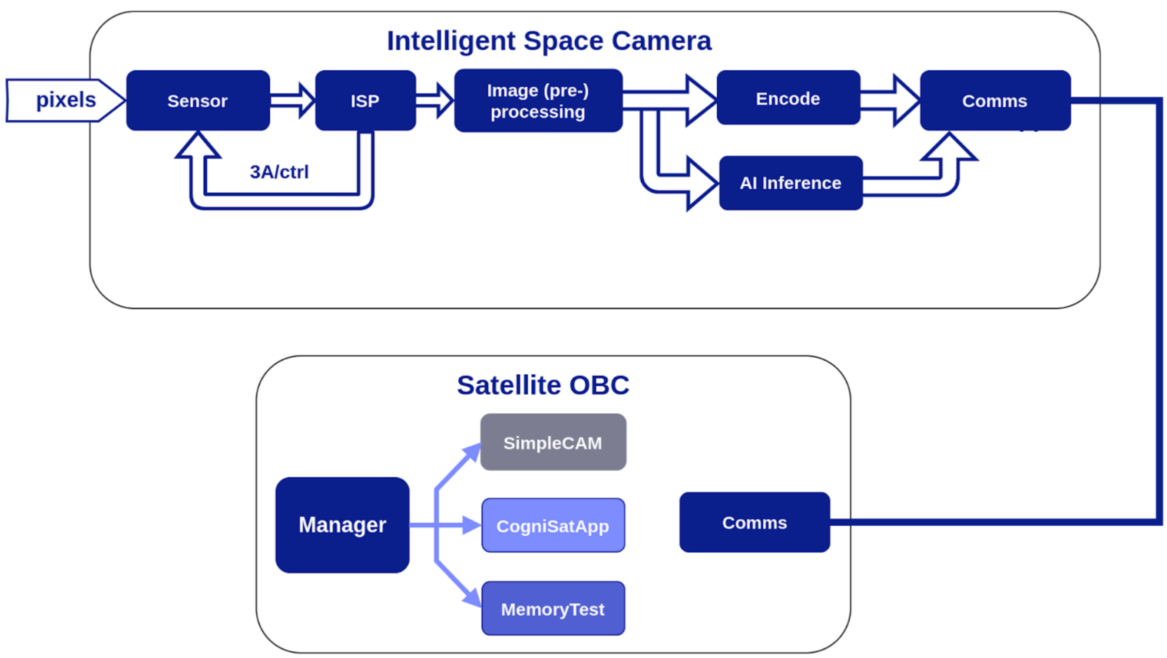

Figure 3: System Architecture

The manager also handles system logging. The manager itself is called by the flight software of the spacecraft executing on the system co-processor (OBC).

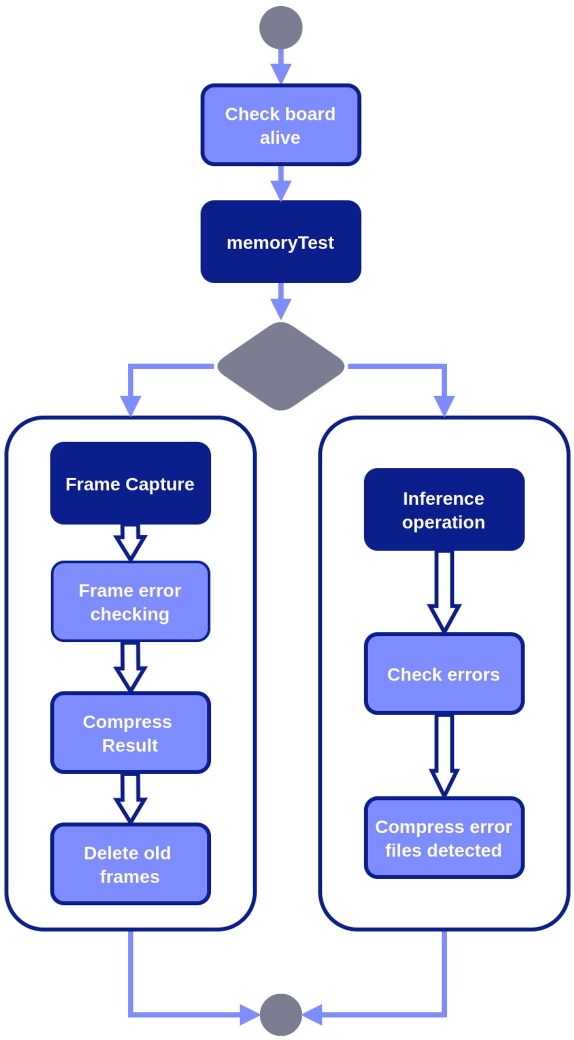

Figure 4: High-Level Manager Functional Flow

To invoke operations that are more computationally intensive, optimized and compiled applications are called by the manager. There are three compiled applications running on the co-processor that controls the ISC. These applications are SimpleCam, CogniSatApp, and the MemoryTest.

CogniSatApp

CogniSatApp is an application that enables the execution of AI inference and image processing operations on the ISC processing board. CogniSatApp makes use of JSON configuration files to allow for easy deployment of new applications in a zero-code manner. The design of CogniSatApp addresses pre- and post-processing generically, allowing for zero or multiple pre-processing operations to be deployed.

SimpleCam

SimpleCam is an application designed to configure the camera to capture frames. Once the custom firmware has booted and is running on the ISC board, frames can be requested from the host side using SimpleCam. The application can configure the board to process the frame through an ISP so RGB images are generated, or to capture frames in Bayer format. SimpleCam also supports frame capture in a loop to acquire video sequences.

MemoryTest

MemoryTest is an application that is executed before each inference or frame capture operation to test that the SDRAM memory on-camera is fully functional.

All three applications generate logs during execution that are available for downlink and on-ground verification. The manager also supports integrated compression, configurable via JSON, of captured frames. Together with the manager, the compiled applications enable an extensive gamut of applications to be executed on the camera simply by uplinking application-specific JSON files to the spacecraft.

Conclusion

The Ubotica Intelligent Space Camera is a novel system that incorporates hardware-accelerated deep learning and image processing in a single, designed-for-space, imaging payload. It can be used for a range of both existing and new applications in space systems, ranging from navigation and scouting for Earth Observation to situational awareness and rendezvous, among others. Since the instrument includes image processing and AI analysis directly at the source (on the sensor), it enables distributed compute architectures for vision systems on spacecraft. This improves efficiency, reduces compute requirements, and provides redundancy. The ISC is currently in orbit and throughout the completion of the activities presented in this paper will reach TRL 9.

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