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Abstract

Earth Observation spacecraft play a pivotal role in various critical applications impacting life on Earth. Historically, these systems have adhered to conventional operational paradigms, namely the “mow-the-lawn” and “bent pipe” approaches. In these paradigms, operational schedules are formulated on the ground and subsequently uploaded to the spacecraft for execution. Execution involves either systematically acquiring vast amounts of data (mow-the-lawn) or targeting specific areas of interest as defined by end users or operators. We aim to depart from these traditional methodologies by integrating onboard Artificial Intelligence, real-time communication, and new observing strategies in one system called CogniSAT-6. These transformative innovations will amplify the amount, speed, and quality of the information yielded by such a system by up to an order of magnitude. Consequently, these advancements are poised to revolutionize conventional Earth Observation systems from static entities into dynamic, intelligent, and interconnected instruments for highly efficient information gathering. This paper provides an overview of the current state of the art in autonomous Earth Observation spacecraft and the application of onboard processing in Earth Observation spacecraft. An overview is given of the CogniSAT-6 mission, its concept of operations, system architecture, and data processing design. Since we believe that the technology presented here will have a significant impact on society, an ethical framework for such systems is presented. Finally, the benefits of the technology and implications for EO systems going forward are discussed.

The Next Era for Earth Observation Spacecraft: An Overview of CogniSAT-6

David Rijlaarsdam, Tom Hendrix, Pablo T. Toledano González, Alberto Velasco-Mata, Léonie Buckley, Juan Puig Miquel, Oriol Aragon Casaled, and Aubrey Dunne

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***Index Terms*—Earth Observation, Onboard Processing, Artificial Intelligence, New Observing Strategies, Real-Time Insights.**

I. Introduction

SATELLITES have been utilized as remote sensing systems since the very beginning of spaceflight itself with the launch of Sputnik in 1957 [1]. While these spacecraft have evolved to smaller form factors and include more capable communication links and more capable sensors, their operational paradigm has largely remained the same. Generally, these spacecraft operate following the static bent pipe principle: commands are sent up, executed on spacecraft and results are sent down.

With the advent of inter-satellite communication links as well as onboard processing, it is now feasible to break with this operational paradigm. By including new processing capabilities on remote sensing spacecraft, captured data can be interpreted at the edge. This allows the spacecraft to react to its environment and make autonomous decisions based on what it ”sees”. In addition, by including a relay communication link information can be delivered to the ground in real-time without requiring line of sight with a ground station. This real-time information delivery is crucial in use cases such as emergency response. Finally, relay communication allows for communication and collaboration with other spacecraft and with sensors on the ground, enabling New Observing Strategies (NOS) and dynamic decision-making based on information from outside of the context boundary of the spacecraft itself.

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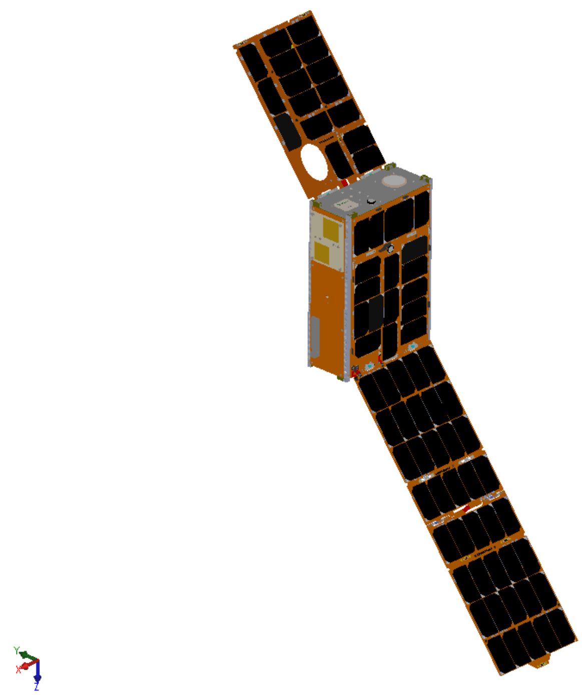

Fig. 1. CAD drawing of CogniSAT-6.

CogniSAT-6, shown in Figure 1, is the first spacecraft specifically designed around this new operational paradigm of autonomous and collaborative robotic remote sensing systems. The CogniSAT-6 is a joint mission from two companies: Ubotica Technologies and Open Cosmos. The spacecraft is a 6U CubeSat that will be launched in a Sun Synchronous Orbit at around 500 km altitude in 2024. It carries a hyperspectral imager as well as an Inter-Satellite Link (ISL) communication payload. In addition, the spacecraft carries the CogniSAT-XE2 Artificial Intelligence (AI) and computer vision edge computing processor from Ubotica. This processing board allows the system to perform inference using neural networks on board the spacecraft as well as complex computer vision tasks. By incorporating both hardware-accelerated onboard AI processing as well as an ISL, the spacecraft can interpret data at the edge, enabling autonomous decisions, collaborative and dynamic operations, and the delivery of information within minutes to an end user. The combination of these capabilities will break with the classical static operational paradigm of current remote sensing systems and increase the return of valuable information from these systems by up to an order of magnitude [2].

This paper first presents a comprehensive overview of related work. Next, an overview of the mission and the concept of operations of CogniSAT-6 is provided as well as an overview of the onboard data processing architecture. Since the authors believe that the technology presented here will have a significant impact on society and autonomous agents such as CogniSAT-6 are moral agents that could encounter ethical dilemmas, a starting point for an ethical framework for such systems is presented. Finally, the implications of the technology integrated into CogniSAT-6 on Earth Observation (EO) systems are discussed.

II. Related Work

The limitations of bent pipe architectures have been well documented in literature, in particular the lack of scalability for large constellations. Denby and Lucia state: *”Limits on downlink bitrate prevent bent pipes from scaling to accommodate the extreme data volumes of large constellations and create a need for a new system architecture less reliant on communication”* [3].

Furano et al. describe the inefficiency of the classical paradigm in [4]. The authors propose applying AI to prefilter data on board, increasing the efficiency of the end-to-end system and moving away from the first-in-first-out bent pipe paradigm. CogniSAT-6 expands on this vision of AI-based space systems by including technologies that enable the system to adapt its operations before image capture, moving from a novel but responsive operational paradigm (images analyzed after capture) to a more dynamic paradigm (previously captured and external information utilized to make informed decisions on upcoming operations and real-time input from the end user).

Chien et al. have proposed the use of EO spacecraft in a ”SensorWeb” [5], where instruments are networked and measurements from one sensor are used to automatically reconfigure other sensors in the web. This system architecture has been demonstrated in the automatic cross-tasking of spacecraft based on measurements from other spacecraft and autonomous tasking based on in-situ measurements of sensors on the ground, showing an increase of event capture by up to an order of magnitude versus blind monitoring of EO spacecraft [6]–[8]. The concept of SensorWebs fits within the larger context of New Observing Strategies (NOS) which has the following goal as defined by Le Moigne and Cole: *”to dynamically optimize measurement acquisition using many diverse observing capabilities (space, air and ground), collaborating across multiple dimensions and creating a unified architecture.”* [9]. CogniSAT-6 addresses this goal of NOS in a small, low-cost and scalable form factor.

Related work has demonstrated elements of the operational paradigm of CogniSAT-6. An overview is given here, detailing related works on onboard processing for EO spacecraft, autonomous scheduling capabilities in EO spacecraft based on captured data, real-time insight delivery capabilities for EO systems, and integration of EO spacecraft in networked sensor systems.

One of the first EO missions to incorporate onboard autonomy was ESA's project for onboard autonomy (PROBA). This spacecraft was launched in 2001 and included onboard payload operational scheduling [10]. The system utilized a constraints solver and optimizer on board the spacecraft to optimize for mission data return but did not interpret captured imagery on board the spacecraft.

The EO-1 mission demonstrated onboard decision-making algorithms that modified the operational schedule of the spacecraft to maximize the scientific output of the system in 2004 [11], [12]. The system, called Autonomous Sciencecraft (ASE), processed captured data to analyze its content and modify the mission plan based on the analysis result with an advanced onboard planner called CASPER. ASE ran on the EO-1 mission until the end of the mission in 2017 [13].

PROBA-2 was launched in 2009 and includes autonomous navigation capabilities [14]. These capabilities included a low complexity numerical orbit propagator, allowing the spacecraft to accurately determine its location even under GPS outages. In addition, the spacecraft can prioritize images based on detected image quality and perform image feature detection on board for coronal mass ejections [15].

PROBA-V was launched in May 2013 and includes an algorithm that predicts land visibility for the instruments [16]. These predictions are used to autonomously switch the instruments on and off. In these autonomous operations, additional constraints based on observation locations and predicted Sun illumination are also taken into account. Arguably, these operations can be considered a form of an ”optimized mow-the-lawn” paradigm.

Launched in December 2013, the 1U CubeSat Intelligent Payload Experiment (IPEX) demonstrated autonomous operations [17]. Like EO-1, the spacecraft was also equipped with CASPER. This system showed how machine learning may be applied to onboard data processing, including the processing of imagery, and how features found in this data can be used to schedule additional acquisitions. However, onboard machine learning techniques did not include neural networks, and the system had limited imaging capabilities due to its small form factor.

On OPS-SAT, a 3U CubeSat by ESA launched in 2019, several relevant experiments have been or are planned to be performed on the spacecraft. An autonomous planner was developed and tested on a ground setup to autonomously reschedule operations based on the output of a classification neural network [18]. NOS-related experiments involving Dynamic Targeting based on interpreting look-ahead image data using onboard processing have been planned for deployment [19]. In addition to these experiments, a range of onboard applications involving processing of captured image data has been performed [20], [21]. The spacecraft also demonstrated the use of ”apps” by abstracting the lower-level implementation requirements from the platform away for app developers [22]. In comparison to CogniSAT-6, OPS-SAT has a relatively limited resolution imager at 80 meter GSD [23]. Furthermore, OPS-SAT's hardware limitations are restricting the compatible neural network topologies to networks that are smaller and less powerful.

An onboard planning system called MEXEC has been developed by JPL [24]. MEXEC was tested in 2020 on the ASTERIA CubeSat [25]. Although this experiment did not use information collected from payload data in its operational planning, it did demonstrate that highly capable planning software may be integrated into a restricted platform like a CubeSat.

Giuffrida et al. describe the Φ-Sat-1 mission in [26]. This was the first spacecraft to include a dedicated AI accelerator on board and utilized a neural network-based pipeline to detect clouds in captured hyperspectral images.

DLR has developed the AMARO (Autonomous Real-Time Detection of Moving Maritime Objects) system, a feasibility study of a real-time alert system detecting ships by processing EO images on board EO platforms [27]. The system utilized the Iridium satellite communication network to transfer alerts in real-time from the platform to the end user. The system was verified in a flight campaign over the North Sea in 2018, but not on spacecraft.

Kerr et al. describe a novel system architecture for EO satellites generating rapid civil alerts in [28]. The authors claim latency of information delivery is below five minutes globally and below one minute in certain cases. Similarly to CogniSAT-6, the authors propose the use of onboard processing in combination with an ISL to provide real-time insights to end users. The authors show that this architecture is both feasible for optical and Synthetic Aperture Radar (SAR) payloads [29]. The proposed system was developed up to TRL 4/5.

HYPSO-1 was launched in January 2023 and includes onboard processing algorithms such as CCSDS123 compression [30]. Implementations for target detection and classification on captured hyperspectral data are planned to be uploaded to spacecraft [31]. While the spacecraft is re-configurable in flight and includes onboard processing capabilities, it relies on line-of-sight communication to a ground station.

Intuition-1 was launched in November 2023 and includes a hyperspectral instrument and onboard processing capabilities [32]. Similarly to HYPSO-1, this spacecraft utilizes its onboard processing to extract information and dramatically reduces the bandwidth required for downlink yet relies on a bent pipe architecture and line of sight communication with a ground station.

Φ-Sat-2 is a 6U Cubesat that will allow developers to run AI apps using the same abstraction framework as implemented on OPS-SAT [33]. Several applications are planned to be deployed to the spacecraft [34]. The spacecraft, due to launch in 2024, will include the Ubotica CogniSAT-XE1 AI accelerator, which includes the Intel Movidius Myriad 2 and a MultiScape100 multispectral camera [35]. The spacecraft does not include a real-time communication link such as an ISL.

To the best of the knowledge of the authors of this paper, no previous mission has combined hardware-accelerated AI processing on hyperspectral imagery, real-time insight delivery over ISL, autonomous scheduling, and real-time user interaction from the ground in one spacecraft system, let alone a CubeSat. While elements of the dynamic, intelligent, and interconnected EO system paradigm presented here have been discussed and in some cases demonstrated in previous work, CogniSAT-6 is the first system to integrate these elements into one platform.

III. Mission Overview and Concept of Operations

As previously stated, CogniSAT-6 has three payloads: a hyperspectral imager, a real-time communication payload in the form of an ISL, and the CogniSAT-XE2 AI and computer vision edge computing processor from Ubotica.

The CogniSAT-XE2 processing board is built around the Intel Movidius Myriad X Vision Processing Unit (VPU), which has been verified for use in space applications in previous work [36]–[38]. CogniSAT-XE2 is further described in subsection IV-A. All payloads, as well as the X- and S-band communication subsystems, interface to the main On Board Computer (OBC). A simplified system diagram is presented in Figure 2.

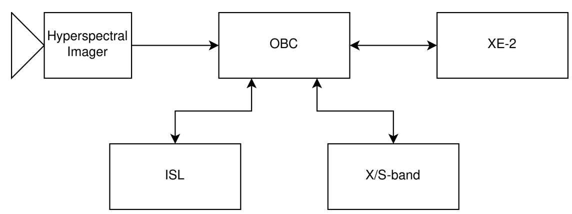

Fig. 2. Simplified system diagram for the space segment of CogniSAT-6.

The mission objectives for Ubotica are:

1) To deliver real-time and persistent insights of value created using onboard AI applications applied to Earth Observation data collected in LEO.
2) To autonomously schedule operations onboard spacecraft based on the output of AI-based data interpretation.
3) To interact with the spacecraft from a consumer device in real-time.
4) To provide a validation platform for new onboard AI and non-AI applications.
5) To provide a platform for offering commercial services to paying customers for Ubotica.

These mission objectives have been addressed by our Concept of Operations (CONOPS), which will be explained in this section. Note that objective 5, providing commercial services, is left out of scope for this paper and will be described in future work.

The initial neural network-based application that has been developed for CogniSAT-6 to execute these CONOPS is a ship detection application, based on a segmentation model. This application is not detailed here, as it should be considered that the system is application agnostic and can be adapted to any feature detection pipeline compatible with the chosen sensor. The authors intend to develop and upload other feature detection applications throughout the mission in addition to the ship detection application and test these applications within the CONOPS presented below. Furthermore, the operational paradigm presented here can be applied to other sensors and spacecraft, therefore the utilized platform is only described at a high level.

A. *Real-Time Insight Delivery (RTID)*

As previously established, current EO spacecraft require a line of sight of a ground station to establish a communication link. Furthermore, this ground station needs to be available to the spacecraft. These constraints can lead to hours or days of latency between image capture and delivery to ground (depending on the number and location of ground stations). Furthermore, these systems do not scale to constellation scale [3], and cannot accommodate the rapid increase of data generated by modern EO imagers [4]. Clearly, this type of system does not meet the first mission objective: insights of value are neither delivered in real-time nor can this solution deliver persistence by scaling the number of spacecraft in a constellation to sufficient numbers.

The current method of alerts creation by EO systems is shown in Figure 3. After image capture, data is downlinked to the ground when possible, where this data is processed to extract relevant information. This information is stored in a database for distribution to end users.

CogniSAT-6 changes this paradigm by moving the data processing operations on board the spacecraft and utilizing real-time communications to distribute the extracted information. This CONOP is shown in Figure 4. Information is extracted from raw data and stored on board in a database. Since this information has orders of magnitude smaller data volume than raw data, an ISL can be used to transmit information to ground. These data links are typically very limited in bandwidth but have the (near) continuous availability required for real-time delivery of information during operations.

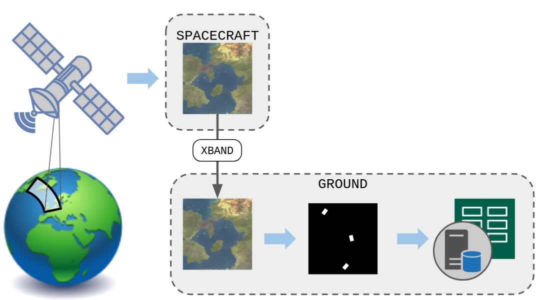

Fig. 3. Concept of Operations for non-real-time delivery of EO-based insights for current EO systems.

Delivering real-time insights of value from EO data is a topic that has been frequently covered in literature recently, a testament to its current relevance. Examples of valuable real-time alerts are: wildfire detection [39], [40], ship detection

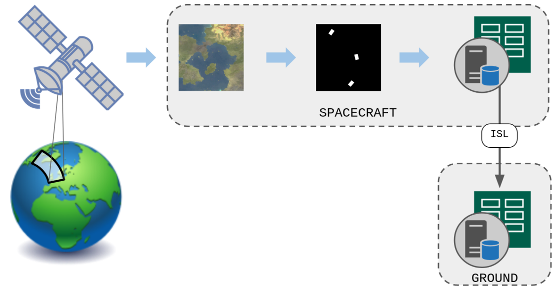

Fig. 4. Concept of Operations for delivery of real-time EO-based insights for AI-centric EO systems.

and extreme weather monitoring [41], flood mapping [42], oil-spill detection [43], detection of Harmful Algal Blooms (HABs) [44], methane emission detection [45], volcanic eruption detection [46] and change detection for disaster management [47].

As stated above, the initial operations of CogniSAT-6 will leverage Ubotica's ship detection application. Output from this application will provide geolocated coordinates of identified ships in an Earth reference frame (longitude, latitude), alongside details on length, width, orientation, and detection confidence. CogniSAT-6 has been designed to deliver insights within 5 minutes from image capture to an end user. An artist's impression of the vision for this CONOP is presented in Figure 5.

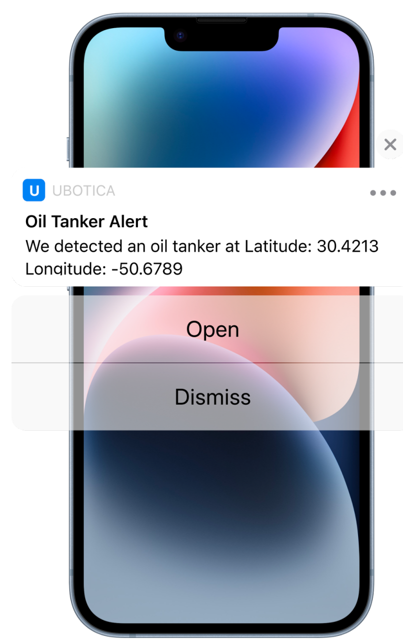

Fig. 5. Artist impression of Real-Time Insight Delivery (RTID) CONOP.

B. *Autonomous Scheduling (ASCH)*

To meet our second mission objective, CogniSAT-6 will autonomously schedule acquisitions based on the detection of features of interest without the need for intervention from ground operators. This operational concept has been previously expounded in [2]. A visual representation of the functional flow of this concept is provided in Figure 6.

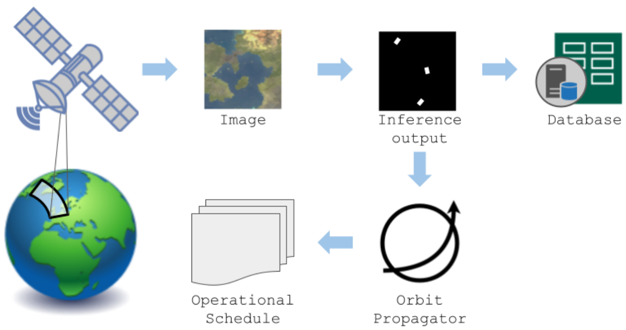

Fig. 6. Functional flow for autonomous scheduling CONOP for CogniSAT-6. Note that all steps presented here are performed on spacecraft.

The concept of operations for this capability can be summarised as follows:

1) The spacecraft flies over a predefined region of interest.
2) An image is captured at the scheduled location using the planned system state.
3) The image is processed in real-time on board the spacecraft to detect and subsequently geolocate features of interest (e.g., ships).
4) If a feature of interest is found, results are stored and an orbit propagator is called. If no feature of interest is found, no action is taken and results are stored.
5) [Optional] If a feature of interest is found, this feature is sent over the ISL directly to the ground to inform mission control.
6) The propagator determines the next opportunity to capture the location of the feature of interest and the required spacecraft attitude.
7) A follow-up image acquisition is scheduled, including the required spacecraft attitude and time of acquisition.
8) The follow-up image acquisition is executed.
9) [Optional] The follow-up image is processed in real-time to detect and subsequently geolocate features of interest (e.g., ships).

As with RTID, in the initial operational phase, the Ubotica ship detection application is used. The system will pass to the onboard orbit propagator the location of the largest detected ship, determined from a single acquisition with a confidence level exceeding 80%. In addition to feature detection applications that detect features other than ships, subsequent operational phases envisage more intricate acquisition logic including sophisticated operational constraints like location-based filtering (e.g., monitoring specific areas), ship orientation-based filtering, ship concentration-based filtering, and others.

Additionally, the proposed system can extend to a tip-and-cue scenario. In this setup, coordinates of the identified feature of interest are sent via ISL to a trailing spacecraft. The receiving spacecraft then employs these coordinates as input for its onboard orbit propagator, expediting the acquisition of this location. The modular structure of the proposed system facilitates the straightforward upload of the developed pipeline to a compatible spacecraft to demonstrate this principle. Experimental validation opportunities for this functionality are being explored.

C. Interactive Satellite (ISAT)

For the third mission objective, the Ubotica Interactive Satellite application will utilize the ISL to enable real-time communication between an end-user device (such as a mobile phone) and the spacecraft. Not only can the spacecraft receive and send information in real-time to both other spacecraft and ground, but it can also interpret the information received in real-time *from an end user* and act on that information.

In the context of satellite operations, it can be argued that it cannot always be determined beforehand which features have the highest value for an end user in specific situations. By leveraging the ISL, the end user can exercise agency by requesting data in real-time. The vision for this operational concept is shown in Figure 7.

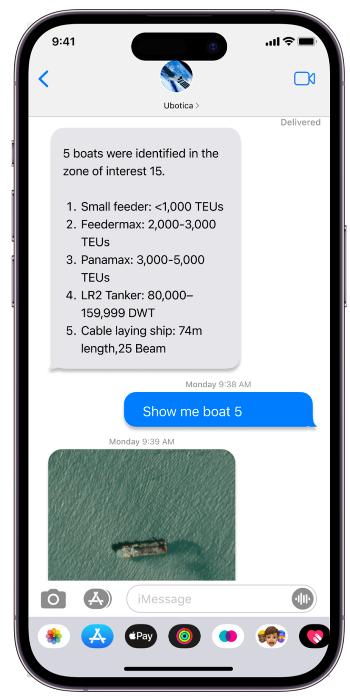

Fig. 7. Artist's impression of Interactive Satellite (ISAT) CONOP.

Here, a push notification is sent from the spacecraft to an end user. The communication is initiated autonomously from the spacecraft, allowing the end user to directly interact with the spacecraft and get responses from the spacecraft in real-time. A "waterfall approach" is taken, where an end user can define from a broad set of captured insights which location, imaging session, and individual insight is of most interest and request that information. In this way, the user can trade off latency for information detail in real-time. The user can decide to utilize the ISL to downlink a thumbnail of a certain insight that is of direct interest, at the expense of receiving broader information on another acquisition at a later time.

In addition to enabling the selection of the most valuable data in real-time, this functionality can also provide a means to enable human oversight in the application of the technologies on board CogniSAT-6.

An operational duty cycle for this CONOP starts with the invocation of the Ubotica ISAT application on spacecraft. Upon starting, the application commences with the downlinking of messages containing a high-level description of the features detected in the latest imaging sessions. As an example, in the ship detection use case, the initial ISL transmission will encompass a summary of onboard inference results, categorized by the port from which they are obtained. The on-ground system operates as an always-on system, enabling continuous retrieval of messages.

When a user connects to the on-ground server with a device, the downlinked messages transition from being stored to being displayed on the GUI on the user's device. Next, the end user can request additional information directly from the spacecraft. When a ground-based request is received by the spacecraft, additional information can be returned to the end user detailing features per image acquisition and providing comprehensive information about a specific feature.

D. Validation Platform

In addition to the specific CONOPS above, CogniSAT-6 is intended as a validation platform for future, as of yet undefined, technologies developed by Ubotica and partners. A key system characteristic required for the validation of new technologies is the ability to a) enable developers to test and iterate on new software for the system and b) apply maintenance to the system by updating existing software and uploading new software.

By developing a representative on-ground flatsat that is remotely accessible to developers, iterative development and verification of operational software is possible throughout the mission lifetime without risk to the spacecraft. In addition to this flatsat, Ubotica enables the development of AI and CV pipelines that run exclusively on the CogniSAT-XE2 processing board by a cloud-based hardware testing platform, allowing third-party developers to develop and verify custom neural networks and computer vision pipelines on representative hardware. Data budgets of the system allow the regular uplink of new software and neural networks.

Several novel onboard experiments have been planned for execution on the spacecraft, which will be published in future work.

IV. Data Processing Overview

CogniSAT-6 is a data processing system that requires novel hardware and software to meet its requirements. These novel elements are described in this section.

A. CogniSAT-XE2

CogniSAT-6 flies the Ubotica CogniSAT-XE2 high-performance AI compute engine, which performs all onboard AI inference for the mission. This platform is a PC/104 form factor board (0.15U) that is ideally suited to the 6U form factor of CogniSAT-6. Weighing 65g, the platform provides Ethernet, USB, CAN, and GPIO communications interfaces to support data communications, command & control, and critical issue identification, respectively. All onboard computations on the XE2 are performed on an Intel Movidius Myriad X Vision Processing Unit (VPU). This is a low-power System on Chip (SoC) with application-specific hardware blocks to accelerate layer computations within inference, and 16 VLIW vector engines for layer compute offloading during inference. The peak power consumption of the XE2 during inference with the ship segmentation network used in the mission is 3.5W, and in low-power standby mode, the board draws only 15mW. The CogniSAT-XE2 engineering model is shown in Figure 8.

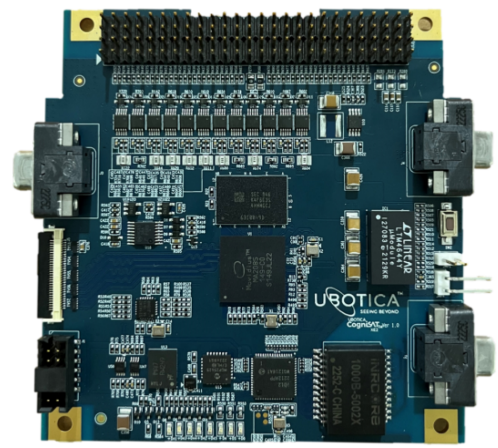

Fig. 8. Engineering model of CogniSAT-XE2.

A custom enclosure from Open Cosmos provides mechanical mounting and an element of radiation protection. The payload power interface is a 5V switched and payload-software-controllable supply from the satellite EPS subsystem supplied via dual redundant connections to the PC104 header array on the XE2.

The XE2 is controlled via Ubotica software, CogniSatApp, which executes on the OBC. This software manages all inference requests, operating in a client-server architecture, wherein the XE2 operates as an inference server that responds to inference requests from the OBC.

On power-up, the XE2 boots from onboard flash memory, automatically loading a secondary bootloader that configures the Ethernet interface and waits to receive the inference application from CogniSatApp. Once received over Ethernet, the application firmware is booted and the board is ready to receive a neural network or PCD (Pipeline Configuration Descriptor), and subsequent inference requests.

Health monitoring is implemented via CSP (CubeSat Space Protocol) status commands over CAN, with lower-level status information acquired through the OBC monitoring of a 1 Hz logic-level heartbeat signal from the XE2. Board errors, for example due to SEEs (Single Event Effects), are managed via an XE2 reboot. A logic level, dual redundant, active high enable signal can be pulled low via the payload software running on the OBC to hard reset the Myriad X on the XE2. This same signal is used to place the XE2 in a low-power mode. Overcurrent thresholds were carefully determined per rail by monitoring current levels on the XE2 power rails during ground testing and adding margin. Overcurrent functionality can be dynamically enabled and disabled during board operation via CSP messages from the OBC. Overcurrent events are automatically handled via onboard power cycling, with re-powering timed from a monostable multivibrator. Any such overcurrent events are logged by the OBC through monitoring of a dual redundant and logic level active high output straight from the XE2.

B. Software Functional Flow

The Ubotica software is controlled by a software orchestrator called a manager. This manager is invoked by flight software, as shown in Figure 9. The manager is in charge of orchestrating the different functional blocks of the application pipeline. The manager is written in Python and invokes optimized and compiled Ubotica C++ applications that perform onboard data processing. In addition to orchestrating the operations of the data processing flow, the manager also handles errors returned from the invoked applications.

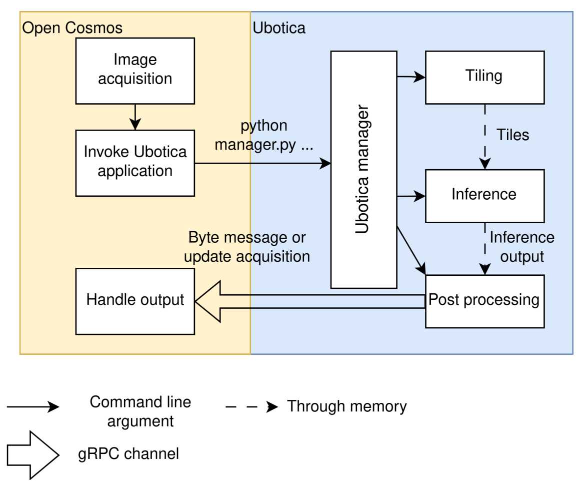

Fig. 9. High-level software architecture depicting both Open Cosmos flight software and Ubotica data processing software.

The software functional flow has been designed to be modular by reusing functional blocks that are shared between CONOPS. Depending on the application, tiling and post-processing may run on the OBC or CogniSAT-XE2.

The software flow begins with the image acquisition by the spacecraft, using the hyperspectral imager. After image acquisition, the Ubotica manager is invoked, triggering the tiler. The tiling application parses and tiles the raw incoming image data from a hyperspectral imager into the expected image format, complying with the input size limitations of the pipeline. Through a JSON file which is passed to the tiling application, parameters such as tile height/width, bit depth, and the number of bands to be included in the tiles are specified. The mapping of an image to individual tiles is shown in Figure 10.

The CogniSAT-XE2 board is controlled by CogniSatApp, an application running on the OBC that enables the execution of AI inference and image processing operations on Ubotica

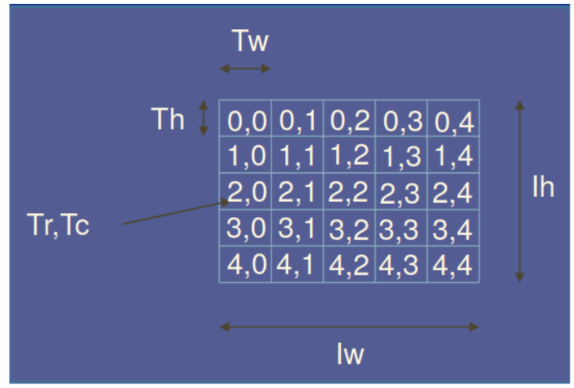

Fig. 10. Mapping of an image to individual tiles. Tw indicates Tile width, Th indicates tile height, Tr indicates tile row, Tc indicates tile column, Ih indicates image height and Iw indicates image width.

hardware. A visual representation of the input to CogniSatApp and the outputs generated are shown in Figure 11.

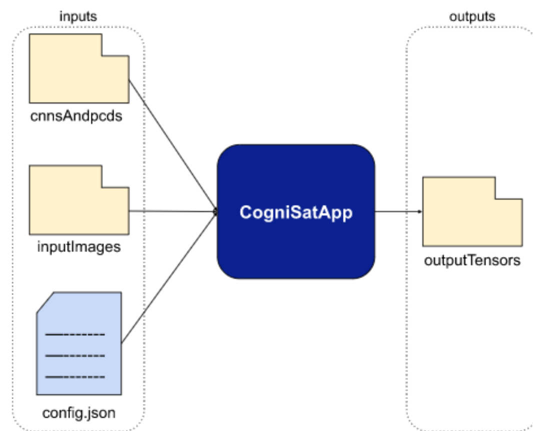

Fig. 11. Visual representation of CogniSatApp dataflow.

CogniSatApp makes use of JavaScript Object Notation (JSON) configuration files to allow for easy deployment of new applications without the need to write/alter any code, and without the need for any compilation. The design of the CogniSatApp addresses pre- and post-processing generically, allowing for zero or multiple pre- and post-processing operations to be deployed in hardware.

Image processing pipelines to be executed require a PCD file that describes the pipelines in binary format. PCD files are generated by Ubotica and have the extension .pcd. Similarly, each neural network to be executed requires a binary file describing that network. Neural Network BLOB files are generated by the Intel OpenVINO tool and have the extension .unn. At least one .pcd file or one .unn file is required to execute CogniSatApp.

The post-processing of the output tensors is performed in parallel with inference to speed up execution times. Depending on the CONOP that is performed, the post-processing software block optionally initiates the ISL connection. Once output tensors start arriving at the post-processing software block output files are immediately handled to improve latency.

For RTID, an ISL downlink is issued immediately when sufficient data is available, reducing the latency induced by waiting for full inference output. The post-processing uses a gRPC channel interface with flight software to queue generated ISL messages for transmission.

For ASCH, after the completion of inference on the entire acquisition, the most relevant feature is chosen as a target for the next acquisition opportunity. As previously stated, for initial demonstrations the most relevant feature is set as the largest detected ship, with a confidence level exceeding 80% The next acquisition opportunity is autonomously determined by the onboard orbit propagator that is part of the Open Cosmos flight software. The autonomously scheduled acquisition can be transmitted over ISL using the gRPC interface to inform mission control.

During ISAT operations, the parsing and processing of incoming and outgoing ISL messages is handled by the manager application. Since the ISAT functional flow does not require any real-time data processing but only retrieves information from an onboard database on request, tiling, inference, and post-processing applications are not invoked.

V. Ethical Framework

Autonomous systems such as the one described here are moral agents that could encounter ethical dilemmas during their application. For example, if the system detects both a forest fire and an oil leak but can only reschedule an acquisition for either of the two features of interest, the decision made by the autonomous system needs to be made on an ethical basis. One could consider this a version of the famous trolley problem [48]. As stated by Tatem et al. in [1]: *"Such a resource [real-time EO] potentially enables revolutionary studies involving the global tracking of ocean life, animals and human movement, which could facilitate, for instance, real-time disease epidemic models, dynamic traffic control and reactive conservation, but it also raises significant security and privacy concerns."*. A similar observation of the need for additional work to define a new perspective on the application of autonomous systems in space activities is made by Martin and Freeland in [49]. Hence, the ethics of these systems must be considered now.

Winfield et al. identify two branches in the field of robot and AI ethics in [50]. Firstly, AI ethics or robot ethics is concerned with the ethical application of such systems in society. Secondly, machine ethics is concerned with the question of how systems such as the one presented in this paper can behave ethically. We will consider the former ethical branch here.

Moor defines machine ethics and methods for incorporating ethics in machines in [51]. Based on Moor's definitions, the technology presented in this paper should be considered an implicit ethical agent and used in society as such, by constraining the system operations to avoid unethical outcomes. To do so, an ethical framework is required. At a high level, unethical outcomes need to be defined to mitigate those outcomes.

Kochupillai et al. define six fundamental ethical values for the application of AI in EO systems in [52]. For each of these values, the authors define an extensive set of ethical issues and guidelines, with examples in the context of *"AI4EO"* based on literature and discussions with peers. These ethical values and associated examples have been used to derive an ethical framework for CogniSAT-6, which is an appendix to this paper.

It should be emphasized that this ethical framework should be considered as a starting point, to be further developed and iterated upon by experts, the scientific community, and society as a whole. We expect that autonomous EO spacecraft, such as CogniSAT-6, will become widely used in society in the coming decades, and therefore stress the importance of practical and sound research to ensure the ethical application of these systems.

VI. Discussion

The technology that is integrated into CogniSAT-6 will transform what EO systems can do by both reducing the operating cost of these systems and increasing the amount of value provided by these systems by orders of magnitude. The CONOPS presented in this paper will demonstrate the capabilities that enable these objectives.

The operating cost of EO systems is significantly reduced by prioritizing or filtering data on board the spacecraft. In doing so, costly system resources such as storage, power and communication bandwidth are saved. In addition, by automating scheduling operations on board the spacecraft the reliance on human operators is reduced. As EO constellations grow, autonomously scheduling operations and transferring locations of targets of interest to other spacecraft using an ISL becomes essential to avoid the costly current bent pipe and mow-the-lawn operational paradigms. Finally, by extracting, storing, and downlinking information rather than raw data, system efficiencies are dramatically increased.

The value created by the EO system is increased by up to an order of magnitude by increasing the speed of delivery of information, by capturing more information of higher value, and by responding more quickly to user requests. By delivering information to end users and responding to user requests in real-time, the inherent value of this information is increased. As an example, receiving an alert within 5 minutes of an otherwise undetected forest fire significantly improves the response time of authorities. More information is captured by removing images that contain no value (e.g. cloudy images) and value within the captured information is ensured by applying AI to detect the presence of valuable information. Current EO systems are ineffective in delivering value in both cloudy regions or regions with sparse information, such as the ocean. CogniSAT-6 can deliver value in those regions by interpreting captured data on board. In addition, by applying NOS and autonomous scheduling capabilities, operational resources can be optimally applied and dynamically reapplied, optimizing system operations for value creation.

In addition to real-time insights, this technology enables *persistent* insights. Persistence of insights is defined as having a minimal time between insights of a single location of interest. This can only be achieved by often repeated measurements of a location of interest. To achieve the required constellation size for this persistence, the unit cost per spacecraft needs to be low. Secondly, operations need to be autonomously scheduled in real-time, and tip and cue needs to be utilized to decrease the effective revisit time of features of interest by autonomously adjusting pointing. Finally, the extracted information needs to be delivered in real-time. CogniSAT-6 shows that all these characteristics can be contained in a single, low-cost, spacecraft.

An important element of the technology presented here is the maintainability and ability to improve the system in flight. To this end, the software can be updated in flight and iterative development is made possible by the availability of a flatsat. The system performance can be iteratively improved over time by updating neural networks and processing pipelines. Furthermore, within the constraints of the flown hardware, entirely new functionalities can be uploaded to the spacecraft over the mission lifetime.

Throughout the mission lifetime, the performance and reliability of the onboard AI will be extensively monitored and analyzed. While operations will initially only send down information extracted from raw data in real-time, all acquired raw data will be sent down at a later time during ground station passes to both enable this performance analysis as well as further development of the onboard software and AI. For autonomous scheduling, AI inference results and scheduled operations will likewise be verified on the ground. By carefully monitoring performance over time, we aim to validate the use of the technologies presented here in prolonged operations. The results of these activities will be published in future work.

VII. Conclusion

EO has tremendous potential to benefit mankind and greatly enhance how we manage our environment, our security, and our economies, helping to address some of the world's greatest challenges. However, EO does not realize this potential today. Spacecraft system design has historically been limited by a lack of capable computing resources. The advent of more powerful edge computing capabilities enables several new operational concepts that were not feasible until now. While these concepts are not necessarily new, they have not been combined in one low-cost platform, nor have they been taken out of the realm of demonstration and to the reality of scalable and repeated utilization in *real use cases*. CogniSAT-6 will, for the first time, take these concepts from demonstration to utilization. The spacecraft marks the beginning of a new era of EO systems: autonomous and collaborative robots that interpret and curate data, make autonomous operational decisions, and can communicate bidirectionally in real-time with other spacecraft and end users. Not only will systems like CogniSAT-6 reduce costs, but they will also provide significantly more value to end users than traditional systems. As onboard computational capabilities and communication bandwidth of ISL systems further improve in the coming years, the capabilities of future systems like CogniSAT-6 will only further increase their value with respect to legacy EO systems and will finally allow a break with the current bent pipe and mow-the-lawn operational paradigms used in EO. With that, EO systems will be able to reach their full potential, improving life on Earth for all.

Appendix
Ethical Framework

This ethical framework has been based on work by Kochupillai et al. [52]. It should be considered a starting point and not finished work, to be further developed with all relevant stakeholders.

- Privacy
  - The data used and generated throughout the development and operation of CogniSAT-6 shall not be tied to individual persons.
  - Data labels shall not contain stigmatizing elements.
  - The system shall not limit individual freedom and self-determination.
  - Ethical risks shall be avoided with respect to privacy (e.g., by not disclosing geolocations in certain situations).
  - The project shall comply with GDPR.
  - Any collection, analysis, or dissemination of data must not adversely impact the fundamental human rights and welfare of people associated with or affected by this data.
- Honesty
  - The shortcomings and limitations of the system and the accuracy of the generated predictions/insights shall be transparent to those who rely on those predictions/insights.
  - If policy decisions are made based on the generated predictions/insights, the process to get to those predictions/insights needs to be made transparent and explainable.
  - The accuracy and correctness of training data, underlying model presumptions and predictions/insights as well as the contextual data veracity is to be considered and tested where required.
- Integrity
  - The system output shall have an accuracy that corresponds to claims made externally.
  - The probability and level of error and uncertainty as well as limitations to the generated prediction/insights shall be determined and disclosed where appropriate.
  - In the context of safety/security data governance shall be considered when making decisions as to the method, extent, and timing of publishing data.
- Fairness
  - Appropriate measures shall be taken to ensure that *equals are treated equally*. For example, while labeling data and while making recommendations regions with similar circumstances should be treated similarly.
  - The system shall operate in an unbiased and nondiscriminatory manner.
  - The system data used in training algorithms shall have the appropriate diversity required for the system

to function in an unbiased and nondiscriminatory manner.

- Responsibility
  - The responsibility for ethical use of the system lies, within reason, with the operator of the system (in this case, Ubotica and Open Cosmos).
  - Human agency and oversight shall be implemented where necessary during the development and deployment of new applications, considering the context in which these applications are to be deployed and the impact that this deployment may have on real people.
- Sustainability
  - The development and operation of CogniSAT-6 shall limit any compromise of economic, social, or environmental sustainability. Where these sustainability prongs need to be balanced against each other, a conscious and responsible decision shall be made with respect to the implementation of this balance taking into account the ethical framework as a whole.
  - The system shall wherever possible contribute to the achievement of the UN Sustainable Development Goals.

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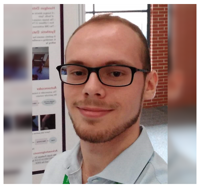

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Dr. Aubrey Dunne is Co-Founder and Chief Technology Officer (CTO) at Ubotica Technologies, a Space AI company with headquarters in Dublin, Ireland. Ubotica specializes in AI processing at the edge, deploying power-efficient embedded solutions in the Space segments. He led the Ubotica team that in 2020 successfully delivered the AI solution enabling the world's first AI inference on board an EO CubeSat. Prior to his role in Ubotica, Aubrey gained 10 years of professional engineering consultancy experience, with companies including Intel and Movidius, in the core areas of computer vision and embedded systems design. Aubrey holds a Ph.D. in Computer Vision, an M.Eng. degree in Electronic Systems, and a B.Eng. degree in Mechatronic Engineering, all from Dublin City University.