SSC23-WII-07

CADENCE: Cubesat Autonomous Detection and Enhanced Networked Computing Experiment

Michael Pham, Zachary Gaines, Pragun Bethapudi, Tarek Elsharhawy
Cal Poly Pomona — ICON Lab
3670 W Temple Ave STE 278 Pomona, CA 91768 USA
mlpham@cpp.edu

ABSTRACT

With the growing proliferation of Earth Observing small satellite platforms, access to remote sensing data has never been greater. Although the collection of remote sensing data has improved significantly, there still exists a significant bottle neck in converting the collected remote sensing data into valuable insights for the end users that need them. In particular a few factors significantly choke the flow of satellite data into insights: limited down-link bandwidth and ground station availability, difficulties associated with responsive tasking, and a general need for human-in-the-loop analysis of the data collected. The proposed CADENCE (Cubesat Autonomous Detection and Enhanced Networked Computing Experiment) mission seeks to develop and demonstrate key technologies to address these three challenges that are currently faced by satellite remote sensing platforms.

By using inter-satellite links and distributed computing resources, the CADENCE mission shall demonstrate the ability to autonomously detect ground-based phenomena, responsively track them, and perform preliminary analysis using Artificial Intelligence algorithms. This notional architecture could support an ad hoc network of combined sensing and compute assets or a hub and spoke model where there the individual satellites are dedicated to sensing or computing but not both. Sensor data can be collected at various nodes and then processed in real time or cross linked to a central hub for responsive analysis. While this preliminary analysis is limited compared to what is possible from ground-based compute resources or human analysts, timeliness is significantly greater. The primary benefit of the on-orbit analysis is the ability to do responsive and ad hoc tasking of a satellite swarm of constellation to observe transient phenomena. In example, an observing satellite could detect the start of a wildfire and autonomously re-task other assets in the constellation to quickly track and gather more data on the fire without the need to complete the loop with human operators, a delay time which makes a significant difference in being able to understand the early stages of transient threats.

The core technologies behind the CADENCE mission are currently being developed by Bronco Space and ICON (the Institute for Collaborative Orbital Networks) at the California State Polytechnic University, Pomona (Cal Poly Pomona).

INTRODUCTION

For the last few years Bronco Space (the unofficial official space program at Cal Poly Pomona) and its affiliate ICON (Institute for Collaborative Orbital Networks) lab have been investigating the use of edge computing to enhance the autonomy of small space systems. This work has manifested in multiple flight projects such as BroncoSat-1 and Bronco Ember which sought to investigate the performance of Machine Learning (ML) compute on orbit and the integration of those compute resources into an autonomous wildfire detection instrument. Additionally, Bronco Space has engaged in experiments with ad hoc inter satellite networks through the Pleiades CubeSat Cluster Program, which itself has yielded 5 amateur band CubeSats launched to LEO to test key subsystems and the use of LoRa radio modulation for coordinated RF networks on-orbit.

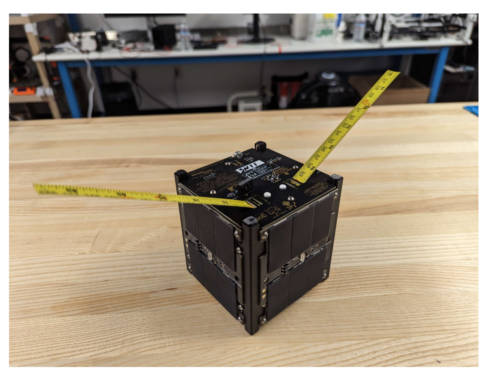

Figure 1: The Pleiades - Squared CubeSat

Experience gained from these flight projects have fed forward into the creation of the CADENCE (Cubesat Autonomous Detection and Enhanced Networked Computing Experiment) concept. The core premise of CADENCE is to create and demonstrate a network of distributed edge computers within a constellation of CubeSats that can provide data analysis and dynamic re-tasking in near real time compared to traditional pipelines. By allowing the assets on-orbit to respond autonomously to transient events, data can be collected and impacts amplified at times when it is most critical. Rather than requiring a collection, downlink, on the ground analysis, retask, uplink loop that can take hours at best and days at worst, we believe a networked system of edge computing satellites could accomplish this in minutes.

RELEVANCE & IMPACT

Within the current state of the art most satellites on orbit, regardless of size, have limited computational power when compared to their terrestrial counterparts. This results in a major bottleneck in a data pipeline, as raw data needs to make its way through downlink channels that often have strict bandwidth restrictions before being processed into useful data products and insights. Within the Earth Orbit operational domain, a delay of even just a few hours for this data capture, downlink, and terrestrial analysis can be extremely costly for missions looking to detect and monitor transient events.

For example, a single satellite in a network of satellites equipped with infrared imagers captures a suspected nascent wildfire during a traditional push broom scan of forested areas. Onboard edge computing would then autonomously classify this detection as a high-risk fire and then rapidly send a high priority data burst to local firefighters through a data backhaul network, notifying them of the most essential information such as estimated size of the fire and approximate fire location.

Through cross links or other communication means, this satellite would also autonomously notify its sister satellites in the detection network to break from push broom scanning and re-task to active tracking of the live fire during their passes, enabling a much larger volume of data collection for a time domain analysis of fire spread and predictive modeling of what methods would be the most effective to fight the fire. This reference use case is currently only possible on timescales of many hours to days, with multiple points of human decision making in the loop to manage to on orbit assets, by which time a natural disaster like a wildfire could have quickly gotten out of hand and valuable data about its inception and initial spread having not it way to first responders or having not been collected in the first place.

Even on Earth, where compute resources are relatively nearby and plentiful, many developers working on autonomous robotics see immense value in having onboard edge compute resources to tighten the loop between autonomous decision-making and robotic action. For spacecraft operating in Cislunar or Deep Space domains, the speed of light becomes a physical limiter to any decision making that needs to have human input. An integrated system that allows for direct autonomy on orbit could greatly accelerate this decision making loop and allow for complex operations such as rendezvous and proximity operations or dynamic scientific tasking to occur far beyond Earth Orbit without the need for meticulous pre-planning.

TECHNICAL APPROACH

Hardware Architecture

A notional hardware stack up for the CADENCE demonstration consists of three elements.

1. A sensing element
2. An edge computing module
3. Satellite cross link capability

These elements are outlined in **Figure 2**. A nominal flow between these elements consists of the sensor taking in data, then that data being processed in real time by the edge computer, an analysis being rendered, key data being sent over the inter satellite link, and dynamic re tasking based on the cross linked data if a high priority target is detected. Data from the sensing element can either be processed directly by the edge computers contained within each CubeSat or it can also be cross linked to offload compute to other elements of the network. This mirrors the system of micro services that has become popular in many modern software tech stacks, providing greater resilience by spreading mission responsibility across multiple nodes rather than concentrating it in a monolithic architecture.

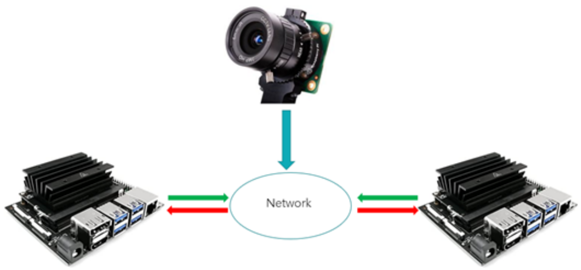

Figure 2: Simplified Hardware Topology

Seen in **Figure 3** is Bronco Ember,[2] which is Bronco Space's high altitude flight tested autonomous wildfire detection instrument. Through the use of a Shortwave Infrared (SWIR) camera, a visible context camera, and a 2 degree of freedom gimbal, Bronco Ember is able to pan and scan through an area to detect nascent wildfires. With the ability to collect up to 300 frames per second from the SWIR imager, there would be no way for this system to downlink all of its data for manual analysis in any reasonable amount of time. An NVIDIA Jetson single board computer therefore provides the edge computing component that enables on-board processing of the data stream created by the camera system.

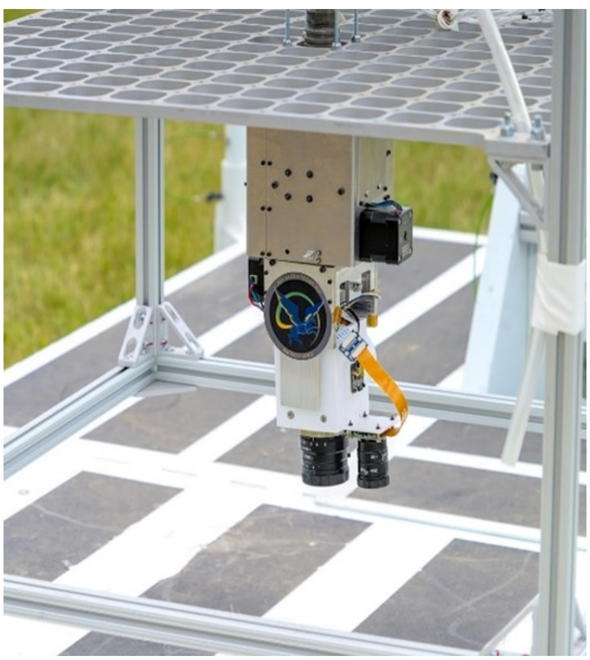

Figure 3: Bronco Ember's First Test Flight

Through the use of edge computing, the system is able to autonomously identify potential wildfires and provide a geolocation without the need for any human engagement. **Figure 4** shows a bounding boxed SWIR hot spot from Bronco Ember's first flight. An approximate lat / long coordinate for this hot spot is also generated based on the position and orientation of the imager. For the Bronco Ember test flights this information is simply down linked to ground operators to verify the validity of the suspected fires. For the proposed CADENCE demonstration, this information would then be cross linked to the trailing satellite to re-task it for a secondary observation. This secondary observation can provide essential temporal data and resolve ambiguities that may have been arisen from the primary observation.

Figure 4: Bronco Ember's First Test Flight

The presence of edge computing resources is an essential aspect of the autonomous architecture, by providing the ability for near real time analysis of incoming data. The use of GPU acceleration can greatly enhance embedded capabilities in this regard. In example, using the processor flown on the Mars Ingenuity Helicopter a YOLO computer vision algorithm could process approximately 4 images per second. Using the latest NVIDIA Jetson platform an identical algorithm could process approximately 1,400 images per second which is a powerful metric when considering the compact size requirements of a CubeSat.

Software Architecture

The ICON Lab has a history of developing and implementing Machine Learning software that neatly fits into CADENCE's mission of intelligently performing lower-level analyses of the remote sensing data collected. In example, Bronco Ember utilizes Machine Learning software to accurately detect nascent wildfires with a targeted accuracy rate of 80 - 90 percent. While the current software is tailored towards wildfires, it can be trained to detect other natural, transient phenomena or human activity.

This is one of the most fundamental benefits of deploying Machine Learning algorithms on orbit assets via edge computing resources. One of the major blockers to this application is the limited data sets available to train reliable and verifiable machine learning algorithms for this application. All of the training data that could be used can be generated on orbit with existing assets, it is just gated behind the inherent limitations of downlink bandwith. By placing a machine learning asset on orbit next to where the data is being created, this algorithm can train itself on a much larger real world data set than is possible on Earth.

In the present day of Neural Networks, the most well-known type of architecture that is used for image segmentation is Convolution Neural Network (CNN). A Convolution Neural Network's bread and butter is in its Convolution layer(s) where the majority of computation is done for image analysis. A type of CNN that is used for image analysis is known as U-Net whose architecture can be seen in Figure 4 and is used for Ember. U-Net comes under semantic image segmentation rather than instance segmentation. Although its main application stems from biomedical image analysis, it can be used for various other applications such as geo-sensing or remote sensing. Compared to instance segmentation, semantic segmentation gives every pixel in an image its own object class. Semantic segmentation is preferred in remote sensing since the pixel of an image is likely to be a range of object classes and at its altitude, a few pixels across a screen can, for example, be a transient, natural phenomenon such as a wildfire.

The U-Net architecture gets its name from its shape as seen in Figure 5. It has an encoder-decoder architecture where the left side of the "U" is a contracting path (encoder section) and the right hand side is the expanding path (decoder section). The encoder section is mirrored from a traditional CNN in which useful information and features from the image are extracted and the decoder section takes these useful features and upsamples the image with the useful features and outputs it.[1] This encoder-decoder feature of the U-Net architecture makes it useful for the rapid detection of transient events such as natural phenomena or human activity. It is also useful in the domain of remote sensing since valuable information is often stored in a couple of pixels on an image.

This type of architecture comes with its own advantages compared to its traditional CNN counterparts. It can learn with very little training data which comprises of few labeled images. It also doesn't require as much time for training compared to its traditional CNN counterpart to learn and perform image analysis. By using U-Net, CADENCE can accurately and rapidly detect an event.

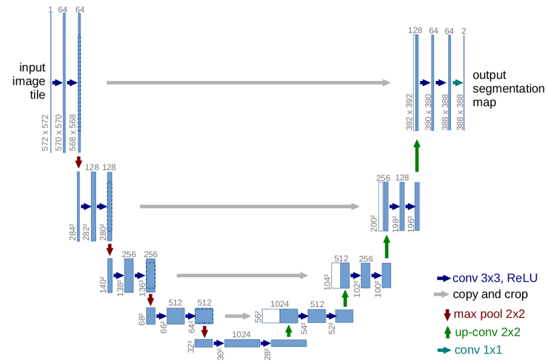

Figure 5: U-Net Architecture

PROPOSED DEMONSTRATION MISSION

CADENCE is currently under development as an integrated demonstration of autonomous detection and re-tasking abilities between two 3U CubeSats. Continuing from the pedigree established by Bronco Ember, the CADENCE demonstration mission would be designed around the premise of detecting wildfires and rapidly notifying the relevant authorities with the most critical information. In this demonstration one satellite would be dedicated to the task of conducting primary observations while the other trailing satellite remains available to dynamically re-task itself to conduct secondary observations. Both satellites would be equipped with an inter-satellite link to facilitate the re-tasking operation. If the inter-satellite link is of sufficient bandwidth it can also be used to cross link collected data to distribute the computing load across multiple processors.

The CADENCE satellites shall build on the flight heritage established by previous Bronco Space flight projects. The inter satellite link can be facilitated by a LoRa modulated signal, which allows for extremely power efficient data transfer while also making use of the the LoRa modulation's spreading factor orthogonality to create virtual channels that allow for multiple simultaneous transmissions to occur on the same frequency without interference.

Seen in **Figure 6** is the Preliminary Design for BroncoSat-4, a 6U CubeSat that has the capability to do multi spectral imaging, edge computing, an inter-satellite link, and 3-axis attitude control. Although this system was originally intended to be used as a component of a Rendezvous and Proximity Operations demonstration mission, we shall use it as a point design for the CADENCE demonstration mission. An important aspect to redesign will be the form factor, condensing the architecture into a 3U, so it may fly as a pair within the scope of the NASA CubeSat Launch Initiative CSLI program.

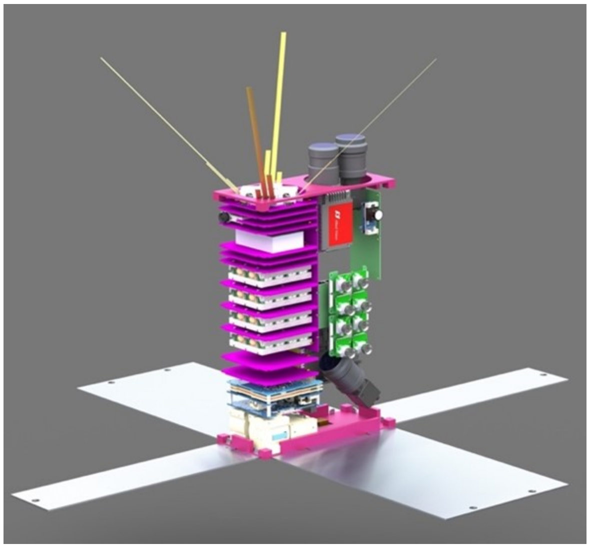

Figure 6: Notional BroncoSat-4 Model

ESTABLISHED WORK

The ICON Lab and Bronco Space have had multiple relevant flight projects that act as a pedigree for the CADENCE mission. The first being Bronco Ember, an autonomous wildfire detection instrument, followed by MoonFALL (the Moon Fast and Accurate Lidar Localization), which uses an AI algorithm to assist with lunar landing. Bronco Ember is at a TRL6 following a sub-orbital test flight in Summer 2022. MoonFALL is expected to also reach TRL6 following sub-orbital test in Q2 2023. Notably, both technology programs reflect a change in TRL from 3 to 6 in approximately 10 months, following the NASA Flight Opportunities office's unofficial motto "Changing the Pace of Space."

PROVES, an educational satellite kit that has been completely led and built by students at Cal Poly Pomona. Bronco Space ICON has also been actively trying to demonstrate inter-satellite links with the Pleiades series of satellites built in collaboration with the Stanford Student Space Initiative. These inter satellite link experiments are intended to demonstrate capability for collaborative multi-point data collection and enhanced in-space situational awareness for small satellites. In January 2023, Pleiades – Yearling and Pleiades – Sapling Sempervirens were launched to LEO to test LoRa based inter satellite links but were unable to deploy due to an issue with the host vehicle. Pleiades - Yearling 2.0 and Sapling - Giganteum launched successfully in April 2023. A successful acquisition of signal was made to both satellites, but Yearling 2.0 suffered an end of mission failure shortly after commissioning. Pleiades - Squared is set to be launched in June 2023 to replace Yearling 2.0 and provide the necessary node for verifying the inter satellite link demonstration.

CONCLUSION

The Cubesat Autonomous Detection and Enhanced Networked Computing Experiment (CADENCE) is a proposed demonstration of collaborative satellites detecting and autonomously observing transient Earth based phenomena. By deploying edge computing resources and an inter satellite link, we believe that CADENCE can fulfill one of the core promises of the CubeSat, that being the ability to make quantity a quality all of its own. Although constellations of SmallSats are rapidly proliferating for Earth Observation, without on-board autonomy they are simply filling niches that were previously untapped by traditional monolithic architectures. If successful, CADENCE shall provide a pathway for a new way of operating of autonomous networking on-orbit.

Acknowledgments

We would like to acknowledge our benefactor, Mike Beckage, for enabling the innovative research conducted at the ICON lab over the last year. Additionally, the support of the NASA Flight Opportunities Office in enabling the development and test of Bronco Ember through the Tech Leap Prize has been an indescribably valuable investment in this research.

References

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