Autonomous Space Domain Awareness for Small Satellites Using Integrated Optical Imaging and Hardware-in-the-Loop Simulation

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***Abstract*—**The increasing density of the orbital environment is driving demand for distributed, autonomous Space Domain Awareness (SDA) capabilities that reduce reliance on ground-based surveillance infrastructure. This work presents an integrated Autonomous Optical SDA Framework combining Infinite Orbits' autonomous onboard perception software with Redwire's flight-representative optical sensing hardware and hardware-in-the-loop validation infrastructure. The demonstrated architecture integrates synthetic orbital scene generation, physical optical acquisition using Redwire's Sentinel-CAM platform, and edge-based autonomous processing for resident space object detection and tracking. A hardware-in-the-loop demonstration was conducted using synthetic unresolved target imagery presented through a representative optical acquisition chain and processed in real time by Infinite Orbits' autonomous detection software. Results demonstrate successful autonomous detection and continuous tracking of a target satellite within a representative simulated observation environment, highlighting the feasibility of compact multifunction optical sensing architectures for distributed SDA applications. This work provides a practical pathway for maturing autonomous optical SDA capabilities prior to in-orbit deployment.

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1. INTRODUCTION

The rapid expansion of the space economy, driven by commercial satellite constellations, Earth observation missions, and increasing spacecraft deployment in Low Earth Orbit (LEO), has significantly increased the operational density and congestion of the orbital environment. Alongside operational spacecraft, the growing population of orbital debris and uncooperative resident space objects (RSOs) presents substantial challenges for spacecraft safety, collision avoidance, mission assurance, and long-term orbital sustainability. These developments have elevated Space Domain Awareness (SDA), also commonly referred to as Space Situational Awareness (SSA), into a critical enabling capability for modern space operations.

Conventional SDA architectures rely primarily on ground-based radar and optical sensor networks to detect, track, and characterize resident space objects. While these systems remain indispensable, they are inherently constrained by atmospheric interference, weather conditions, geographic coverage limitations, revisit gaps, and communication latency. As orbital traffic density continues to increase, these centralized architectures face growing scalability challenges, particularly for responsive mission scenarios requiring rapid local decision-making or autonomous operations.

Recent advances in miniaturized optical sensing, onboard computing, and autonomous perception algorithms have created new opportunities for distributed, space-based SDA architectures deployable on small satellite platforms [1], [2], [3]. Optical sensors are particularly attractive for such applications due to their passive operation, low power consumption, compact form factor, and compatibility with CubeSat and small satellite size, weight, and power constraints [1], [3]. At the same time, progress in onboard autonomy is enabling spacecraft to transition from passive sensing nodes toward intelligent platforms capable of independently detecting, tracking, identifying, and characterizing nearby space objects without continuous dependence on ground infrastructure [4], [5], [6], [7].

A key challenge in realizing such capabilities lies in the integration burden associated with conventional sensor architectures. Traditional spacecraft often rely on separate payloads for imaging, attitude determination, and situational awareness, increasing system complexity, calibration requirements, processing overhead, and overall spacecraft resource consumption. These constraints are particularly significant for small satellite platforms, where SWaP budgets severely limit the practicality of dedicated multi-sensor surveillance architectures. Recent advances in multifunction optical systems, including dual-use imaging and star tracking architectures, provide an attractive pathway toward reducing this burden while preserving mission-critical sensing capability.

Redwire has developed a family of compact, flight-proven optical sensing technologies designed for spacecraft attitude determination and imaging applications. SentinelTRAC provides high-accuracy spacecraft attitude determination in a compact, low-power package suitable for CubeSat, small satellite, and larger spaceflight applications, while SentinelCAM provides high-resolution optical imaging adaptable to a range of mission scenarios. Complementing these sensing platforms, Redwire's SentinelSIM hardware-in-the-loop star field simulation infrastructure enables controlled laboratory generation of representative celestial scenes for realistic end-to-end optical system validation.

In parallel, Infinite Orbits has developed autonomous SDA software focused on onboard detection, tracking, and identification of resident space objects through integrated optical perception and real-time onboard processing. To support realistic validation of these capabilities, Infinite Orbits has also developed a high-fidelity simulation environment incorporating spacecraft attitude propagation, maneuver execution, sensor modeling, satellite geometry representation, and unresolved image generation.

This work presents an integrated autonomous SDA architecture combining these complementary capabilities. Infinite Orbits' autonomous SSA/SDA software stack is integrated with Redwire's optical sensing platforms and validated through hardware-in-the-loop simulation. Two complementary optical sensing configurations are investigated. The first integrates the autonomous detection and tracking software with Redwire's SentinelTRAC star tracker using Redwire's SentinelSIM star field simulator to generate representative celestial and orbital scenes for controlled end-to-end validation. The second integrates the software stack with Redwire's SentinelCAM imaging platform, validated using Infinite Orbits' synthetic scene generation and simulation framework.

By combining autonomous onboard SDA software, flight-representative optical sensing hardware, and realistic hardware-in-the-loop validation, this work demonstrates a practical pathway toward scalable, distributed space-based situational awareness for small satellite missions. The results highlight the feasibility of multifunction optical architectures supporting autonomous detection and tracking while reducing dependence on traditional ground-based surveillance infrastructure.

2. LITERATURE REVIEW

Traditional SSA architectures rely predominantly on ground-based radar and optical sensor networks for RSO detection, catalog maintenance, conjunction assessment, and behavioral monitoring [8]. However, such systems are constrained by atmospheric effects, weather conditions, geographic coverage limitations, and revisit gaps, motivating increased interest in distributed space-based sensing architectures for persistent orbital surveillance [7]. This section reviews prior work in optical SDA sensing, autonomous onboard processing, and hardware-in-the-loop validation relevant to the integrated architecture presented in this work.

One promising approach is the use of onboard optical sensors for autonomous RSO detection and tracking. Optical sensing offers passive operation, low power consumption, and compatibility with small satellite SWaP constraints. Recent studies have demonstrated that star trackers, traditionally used for spacecraft attitude determination, can be repurposed as opportunistic SDA sensors. Clemens *et al.* demonstrated the feasibility of using commercial star trackers for on-orbit RSO detection [9], [10], while Dave *et al.* expanded this concept through the RSOnet framework, enabling autonomous detection and classification using dual-purpose star tracker imagery [1]. Additional in-space demonstrations and star tracker-based measurement methods have further validated the viability of extracting SDA information from flight-qualified attitude sensors [2], [11], [12].

Beyond opportunistic star tracker sensing, dedicated compact optical payloads have also emerged for SDA applications, reinforcing the shift toward multifunction sensing architectures compatible with small satellite SWaP constraints [3], [13]. This trend aligns with broader spacecraft sensing architectures that seek to reduce hardware redundancy while preserving mission-critical imaging and navigation capability. In parallel, advances in autonomous detection and tracking algorithms have expanded onboard SDA capabilities. Machine learning-based approaches have demonstrated improved detection performance for RSO observations under complex imaging conditions, while event-based sensing architectures offer computationally efficient alternatives for real-time tracking [14], [15], [16].

Autonomous onboard processing is another key enabler for next-generation SDA architectures, reducing dependence on ground-centric processing and mitigating communication latency and scalability constraints. Recent work has demonstrated the feasibility of onboard inference for RSO detection, including edge AI deployment and autonomous sensor tasking for adaptive observation strategies [4], [5], [6]. Broader SDA studies have also highlighted the complementary advantages of space-based sensing, including improved persistence, reduced atmospheric interference, and access to observation geometries unavailable from Earth [7], [17]. Related work has further shown that optical object observations can support not only situational awareness but also autonomous navigation, reinforcing the broader value of multifunction onboard perception systems [18].

Realistic validation remains a critical enabler for autonomous SDA systems, as flight experimentation is costly and high risk. Hardware-in-the-loop (HIL) simulation has therefore become an essential verification approach, particularly for optical sensing systems. Prior work has demonstrated real-time HIL validation of star trackers and vision-based navigation systems using optical simulators and synthetic scene generation [19], [20], [21], [22]. More recent efforts have expanded toward higher-fidelity synthetic orbital scene generation, including opportunistic sensor calibration and simulated RSO observations under representative imaging conditions [23], [24]. These developments provide an important foundation for validating autonomous optical SDA concepts under controlled but operationally representative conditions.

Despite this progress, most prior work addresses sensing hardware, autonomous detection algorithms, onboard processing, or HIL validation as largely separate problem domains. Comparatively limited work has demonstrated fully integrated end-to-end autonomous SDA architectures combining flight-representative optical hardware, realistic orbital scene generation, autonomous onboard detection and tracking, and closed-loop HIL validation within a unified framework. In contrast, the approach presented here combines multifunction optical sensing hardware, autonomous onboard SDA software, and complementary simulation-based validation environments to assess integrated end-to-end system performance under representative operational scenarios.

3. AUTONOMOUS OPTICAL SDA FRAMEWORK

This section introduces the proposed Autonomous Optical SDA Framework and its key enabling components. The framework combines flight-representative optical sensing hardware, autonomous onboard detection and tracking software, and complementary simulation-based validation environments to enable end-to-end evaluation of autonomous SDA capabilities. Key elements include Redwire's optical sensing platforms and hardware-in-the-loop star field simulation infrastructure, together with Infinite Orbits' autonomous SDA software and synthetic orbital scene generation environment. Collectively, these capabilities establish a representative testbed for evaluating integrated autonomous optical SDA performance in controlled yet operationally realistic conditions.

SentinelTRAC-2 Overview

Redwire's SentinelTRAC star tracker has achieved significant flight heritage, with over 100 first-generation units (SentinelTRAC-1) currently operating in orbit and many more being integrated across various missions. The second generation SentinelTRAC-2 builds on lessons from the first-generation units and offers a robust star tracking algorithm suite.

- Dimension: 120x61x61 LxWxH (mm)
- Weight: 475g (w/ 45 deg. SEA baffle)
- Operating Temperature: -30C to 55C
- DC voltage: 5.0 V
- Average power consumption: 2.5 W
- Lens: 22 mm Aperture, F1.2 BK7 Glass
- Serial Interface: RS-422

Table 1. SentinelTRAC-2 specifications

Descriptor	Specification
Resolution	1296 x 972 pixels
Update rate tracking	8 Hz
Max tracking angular rate	2°/sec
Sun Exclusion Angle w/wo baffle	30°/45°/90°

Figure 1 presents the SentinelTRAC hardware with the large baffle.

After an image is captured, the SentinelTRAC-2 processes it in three sequential stages: centroiding, star identification, and attitude calculation. In the centroiding step, the captured image is analyzed to locate all potential star centroids within the field of view. During the star identification stage, the detected centroids are matched against the on-board star catalog to identify the observed stars in the frame. Finally, the identified stars are used to calculate an attitude estimate for the tracker. It can obtain an attitude solution within 230 ms without prior attitude knowledge and within 170 ms when actively tracking stars. The accuracy metrics for SentinelTRAC-2 are given in table 2.

Table 2. Performance Metrics for SentinelTRAC-2

Direction	1σ accuracy
Cross-axis (XY)	5.1 arcseconds
Roll (Z)	45.0 arcseconds

SentinelCAM-1 Overview

Designed to be a general purpose optical sensor, SentinelCAM-1 provides an ideal solution for scientific observation and imaging of the sun-illuminated orbital environment due to its low-light sensitivity and wide dynamic range. SentinelCAM-1 employs the standard GigE vision protocol, a widely adopted industry standard for machine vision cameras. This protocol provides a framework for transmitting high quality video and control data over standard Ethernet networks, offering benefits such as ease of integration and scalability.

Table 3. SentinelCAM-1 specifications

Descriptor	Specification
Exposure time	100 μs
Resolution	2592 x 1944 pixels
Frame rate	10 Hz

While operating as a 5 megapixel camera (2592 x 1944 pixels), the SentinelCAM-1 is capable of running at a rate of 10 Hz with an exposure time of 100 μs. SentinelCAM-1 can operate with the same lens as SentinelTRAC-2, or the specific lens and focal distance can be chosen to best suit the use case on orbit. If the system is developed to enable both the SentinelCAM-1 and SentinelTRAC-2 to operate on the same optical head, then the lens will be focused for optimal star tracking. If SentinelCAM-1 and SentinelTRAC-2 are configured

Figure 1. SentinelTRAC-2 Flight hardware (120x61x61 mm), including a 45 deg Sun Exclusion Angle baffle.

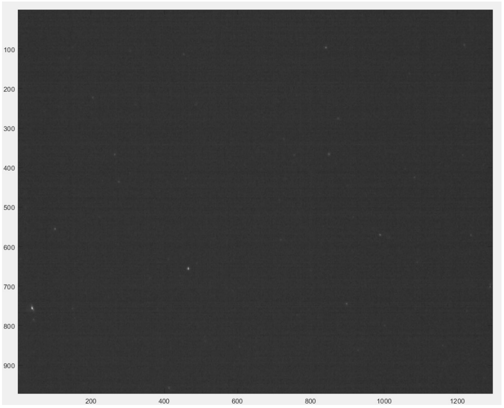

Figure 2. A typical night-sky image capture utilizing the SentinelTRAC-2.

as a dual optical head, then each will have its own lens focused appropriately.

Figure 3. A typical moon image capture utilizing the SentinelCAM-1. Courtesy of Intuitive Machines.

Star Field Simulator

The hardware-based simulations include a display screen that projects images of star fields and a star tracker positioned at a fixed distance away. This configuration enables testing of the entire tracker pipeline- from photon collection and image processing to RSO detection.

The Redwire Space Star Field Simulator is a hardware-in-the-loop simulator that provides as-you-fly operation of the Redwire Star Tracker in a simulated night-sky environment [25]. Figure 4 represents the Star Field Simulator components and structure. The Star Field Simulator features several modes, including predefined flight through user-defined night-sky segments, externally driven orientation used in a closed-loop environment, and prerecorded night-sky tracking data. This flexibility allows the star field simulator to accelerate the entire vehicle flight control development cycle, from initial star tracker integration to complete flight simulations. For example, flight systems engineers can use the star field simulator to evaluate operational scenarios involving different motion rates, vehicle control scenarios, and pointing transitions. In addition to system integration and simulation support, the star field simulator serves a testbed for verifying star tracker operation, saving valuable system troubleshooting labor and schedule time during build and test cycles.

Simulation Environment

To support development, integration, and realistic validation of autonomous SDA capabilities, Infinite Orbits has developed a high-fidelity simulation environment capable of generating representative orbital observation scenarios. The simulation framework models spacecraft attitude propagation, orbital motion, maneuver execution, sensor behavior, and multi-object orbital interactions, enabling realistic end-to-end testing of perception and tracking algorithms under controlled conditions.

A core capability of the simulation environment is synthetic optical scene generation for space-based observations. Satellite geometry representations, illumination conditions, and bidirectional reflectance distribution

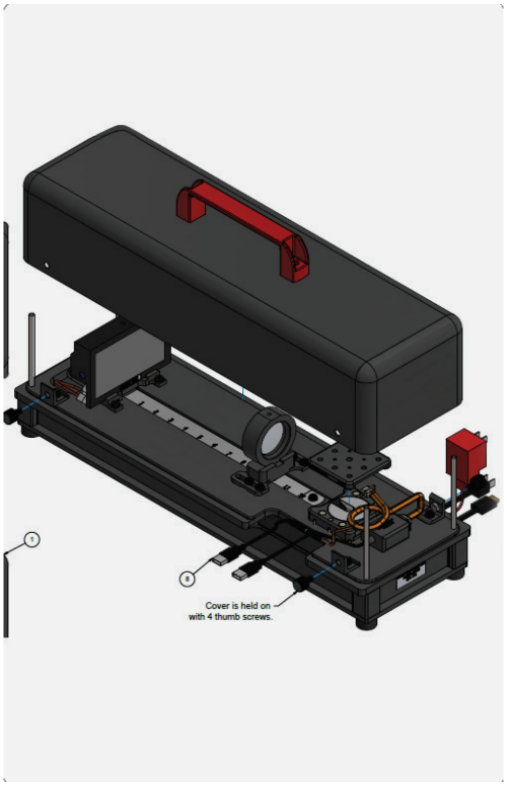

Figure 4. SentinelSIM Star Field Simulator.

function (BRDF) modeling are used to generate physically representative unresolved and resolved imagery of resident space objects. This includes simulation of key optical effects relevant to operational SDA sensing, such as apparent brightness variation, motion blur, streak formation, sensor-specific imaging behavior, and varying observation geometries.

The simulation framework serves both algorithm development and hardware-in-the-loop validation activities. For SentinelCAM integration, synthetic orbital scenes are used to generate representative optical inputs for evaluation of autonomous detection and tracking performance under realistic conditions. This allows repeatable assessment of algorithm robustness across varying target characteristics, lighting conditions, and operational scenarios without the cost and risk associated with flight experimentation.

By combining orbital dynamics simulation, optical scene generation, and sensor-aware image synthesis, the environment provides a representative validation framework for assessing autonomous optical SDA capabilities prior to operational deployment.

Autonomous SDA Software

The autonomous SDA software developed by Infinite Orbits provides onboard perception and analytics capabilities for the detection, tracking, identification, and characterization of resident space objects using optical sensor data. Designed for deployment in space-constrained environments, the software leverages edge-AI and onboard image processing to reduce reliance on continuous ground-based analysis while enabling responsive local decision-making.

As shown in Fig 5, the software architecture supports multiple operational use cases across both SDA and in-orbit servicing applications through a modular perception framework. Within the SDA domain, the ACTIVATE processing chain enables autonomous detection, tracking, and characterization of resident space objects from unresolved optical observations, supporting applications such as space surveillance, tracking, and catalog maintenance through analysis of point-source or streak-like signatures. The SPECTRE capability extends this functionality to resolved imagery, enabling higher-fidelity object identification, classification, characterization, and feature recognition for surveillance and inspection applications. Beyond SDA, the same perception framework supports in-orbit servicing through the VISION module, which enables optical navigation and six-degree-of-freedom pose estimation for rendezvous and proximity operations.

To support onboard deployment, the software is designed with computational efficiency in mind, balancing detection performance with the resource limitations typical of small satellite processing platforms. By combining autonomous perception, object analytics, and adaptable mission functionality within a unified software architecture, the framework provides a scalable foundation for distributed autonomous optical SDA operations.

4. INTEGRATED DEMONSTRATION ARCHITECTURE

The end-to-end demonstration architecture used to validate the proposed Autonomous Optical SDA Framework is illustrated in Fig 6. This hardware-in-the-loop configuration integrates Infinite Orbits' synthetic scene generation and autonomous SDA software with Redwire's optical sensing hardware and image acquisition infrastructure to evaluate the complete perception pipeline under representative operational conditions.

For the unresolved-object SDA demonstration, Infinite Orbits' simulation environment generates synthetic orbital observation scenarios representing resident space objects under representative viewing geometries and operational conditions. These synthetic image sequences are rendered in a continuous loop and displayed on an AMOLED screen integrated within Redwire's shrouded optical sensor test enclosure. By physically presenting the synthetic imagery to the optical sensor rather than directly injecting software-generated image data, the demonstration captures real optical acquisition effects and provides a more representative validation of the sensing chain.

As shown in Fig 6, Redwire's SentinelCAM optical imaging sensor, configured with the representative optical lens assembly, observes the displayed synthetic scenes and acquires image data through the physical

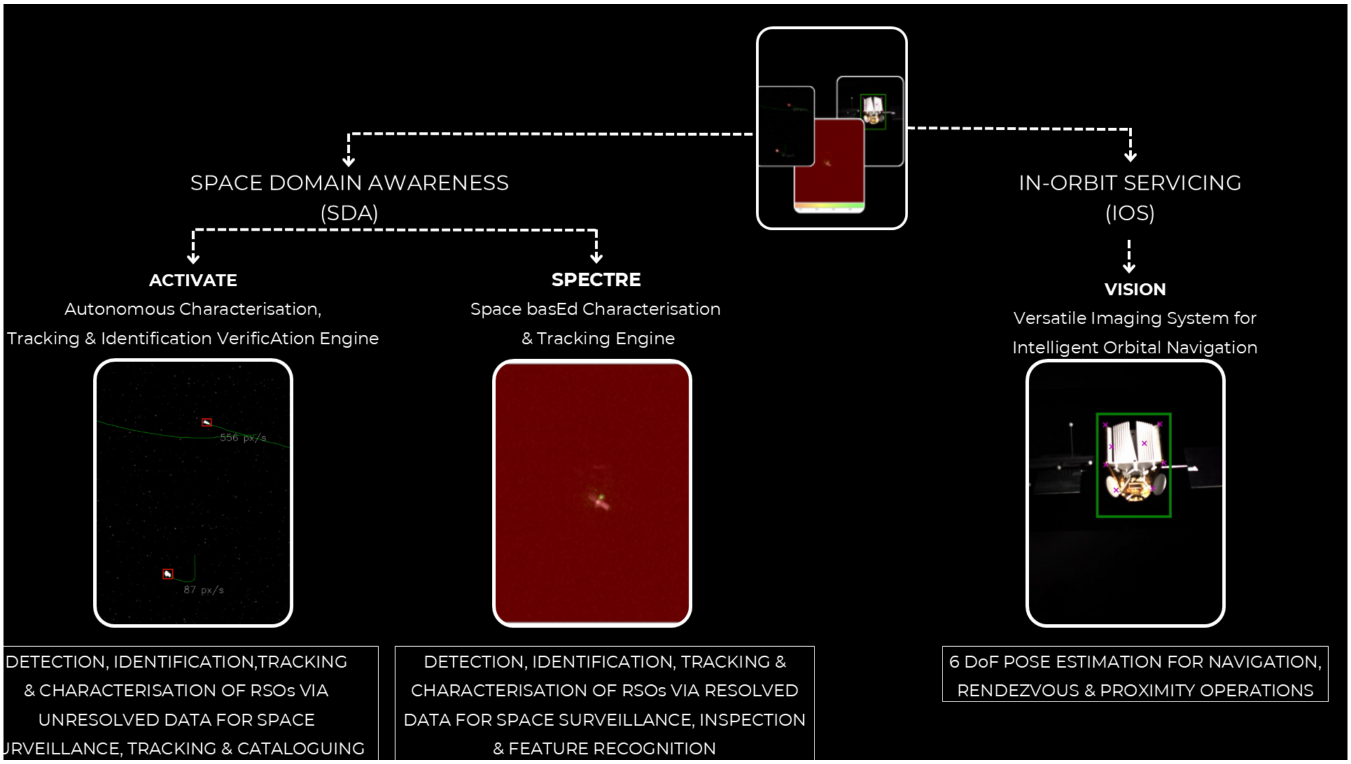

Figure 5. Functional architecture of the Infinite Orbits onboard autonomous perception framework, illustrating SDA and in-orbit servicing operational modes.

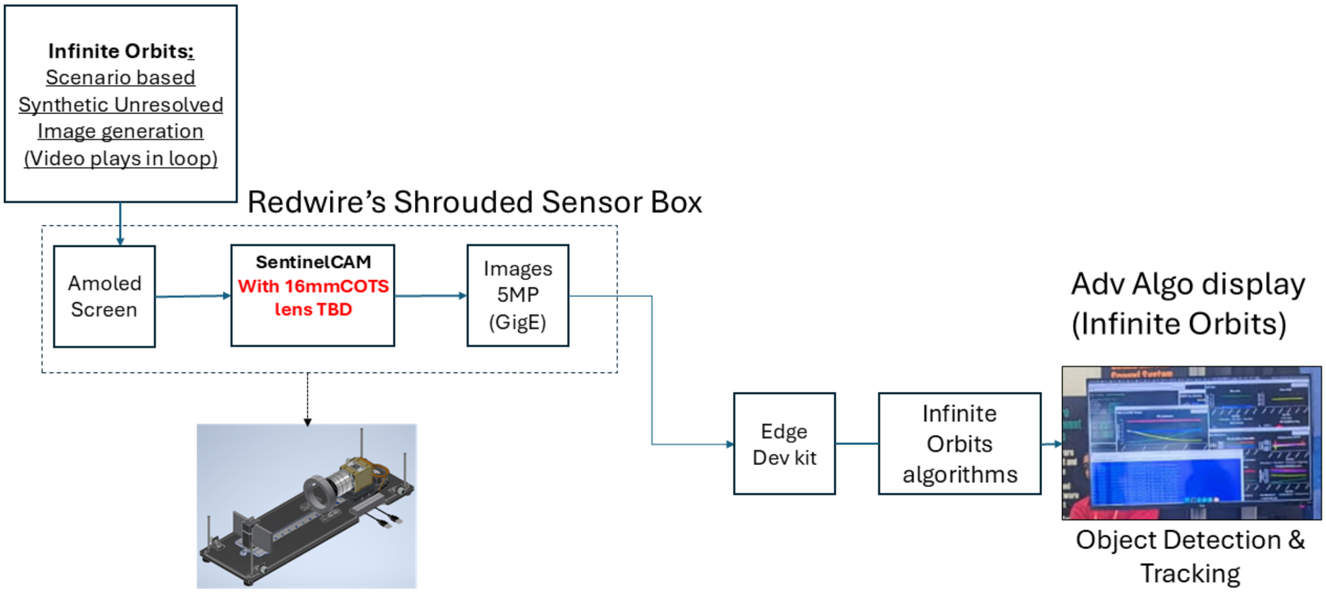

Figure 6. End-to-end hardware-in-the-loop demonstration architecture integrating synthetic scene generation, Redwire optical sensing hardware, and Infinite Orbits autonomous onboard detection and tracking software..

optical path. The resulting image stream is transferred through a GigE image acquisition interface to an edge processing platform executing Infinite Orbits' autonomous SDA software. This configuration enables validation of the complete sensing and processing chain, including synthetic scene generation, physical optical acquisition, image transfer, onboard processing, and output visualization.

During operation, Infinite Orbits' ACTIVATE software processes the incoming optical imagery in real time to autonomously detect and track the target satellite within the synthetic observation scene. Detected objects are identified within the image stream, and associated tracking information is generated and updated continuously as the target evolves through the simulated observation sequence. The processed outputs, including annotated detections and tracking overlays, provide direct confirmation of successful autonomous onboard perception and tracking performance.

By integrating synthetic orbital scene generation, physical optical sensing hardware, real image acquisition interfaces, and autonomous onboard analytics within a closed-loop validation architecture, the demonstration provides a representative testbed for assessing distributed autonomous optical SDA capabilities prior to operational deployment.

5. CONCLUSIONS

This work presented an integrated Autonomous Optical SDA Framework combining Infinite Orbits' autonomous onboard perception software with Redwire's flight-representative optical sensing hardware and hardware-in-the-loop validation infrastructure. The demonstrated architecture enables end-to-end evaluation of autonomous resident space object detection and tracking using synthetic orbital scenes, physical optical acquisition, and edge-based onboard processing.

The hardware-in-the-loop demonstration showed the feasibility of autonomously detecting and continuously tracking an unresolved target satellite within a representative simulated observation environment, highlighting the potential of compact multifunction optical sensing architectures for distributed SDA applications. By integrating realistic simulation, flight-relevant hardware, and autonomous onboard analytics, this approach provides a practical pathway for maturing autonomous optical SDA capabilities prior to in-orbit deployment.

Future work will extend the framework toward resolved-object scenarios, higher-fidelity operational environments, and expanded autonomous identification and characterization capabilities.

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