

Flight Test Configuration of the Sensor Payload and the Ground Nodes in Distributed Sensing Frameworks

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The realization of the Urban Air Mobility (UAM) vision, entailing the deployment of high-density autonomous flights over urban areas, necessitates methodologies transcending contemporary airborne sensing techniques. An instrumental innovation in this realm is the advent of distributed sensing. In this paradigm, environmental sensors function as active agents, engaging in the triad of sensing, processing, and communication either amongst themselves, with ground stations, or both. This concerted effort creates a dynamic and responsive "smart space," facilitating real-time autonomous control. NASA Ames Research Center is actively engaged in a series of comprehensive indoor and outdoor flight tests to garner requisite data and insights essential for the actualization of this ambitious vision. This paper delineates the holistic configuration of the flight payload and the distributed ground nodes pivotal to the NASA flight test campaign. Furthermore, it expounds upon the intricacies of the sensor node communication framework. The narrative extends to provide a detailed overview of the strategic placement of distributed sensors and a comprehensive account of the varied indoor and outdoor flight tests orchestrated in pursuit of UAM objectives.

I. Introduction

NASA's Advanced Air Mobility (AAM) initiative endeavors to establish a secure air transportation system capable of ferrying people and cargo in rural and urban areas through groundbreaking aircraft technologies. Specifically targeting locations historically underserved by aviation [1], AAM envisions a transformative impact on urban transportation through the implementation of Urban Air Mobility (UAM) concepts. UAM envisions short-distance flights facilitating efficient transportation within densely populated metropolitan regions, aspiring to render its technologies practical and cost-effective for alternative transportation modes in these areas [2].

Beyond its immediate goals, UAM concepts harbor the potential to revolutionize urban transportation and contribute to the evolution of smart cities. In the context of smart cities, the conceptual shift involves the pervasive integration of embedded and mobile technologies throughout the urban landscape, interconnected in real-time across multiple communication networks. This infrastructure is designed to furnish continuous data, facilitate analysis, and support automation across various functions and applications.

However, existing critical technologies vital for the safe operation of air transportation systems are inadequately suited for the unique challenges presented by UAM. Consequently, UAM research endeavors to define a set of criteria and functionalities to achieve a safe and fully autonomous system. These include navigating shared airspace with diverse aircraft types, maneuvering through complex urban structures, and executing precise landings in confined spaces atop buildings.

Given that traditional surveillance systems prove impractical for AAM operations and GPS reliability diminishes in urban environments, the reliance on GPS for self-reporting surveillance and navigation becomes untenable [3]. Embracing the concept of Distributed Sensing (DS), the initiative aims to enable continuous, real-time monitoring of physical and environmental conditions through a network of overlapping sensors throughout the flight. DS seeks to establish a framework incorporating geographically distributed (non-co-located) sensors for remote sensing applications for tasks such as surveillance and tracking. It addresses sensor drop-outs due to degradation, ensuring persistent estimates meet minimum quality requirements through continuous quality evaluation from each observation source, employing

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cross-validation and confidence metrics. Transitioning from theoretical considerations to practical implementation, NASA executed a series of tests within their simulation framework last year [4]. Following this, indoor flight tests were conducted as a preparatory step before venturing into outdoor tests.

This paper undertakes a meticulous examination of the structural intricacies of both the airborne payload and ground nodes, strategically distributed to investigate DS concepts. Furthermore, a comprehensive exploration of the communication framework is provided, emphasizing its design principles aimed at minimizing both delay and data loss. The robustness of the communication network is paramount, as it serves as a critical assurance of the system’s safety and security. Drawing insights from both theoretical foundations and hardware specifications, the paper proceeds to present the intricacies of the software implementation. This comprehensive description encompasses the symbiotic integration of software elements with theoretical underpinnings and hardware functionalities. In its final exposition, the paper offers a succinct yet informative overview of the various indoor and outdoor flight tests conducted. These tests serve as critical milestones in validating the conceptual theories, hardware configurations, and software implementations discussed earlier, providing empirical evidence of the system’s efficacy under different operational scenarios.

II. Hardware Architecture

The subsequent section describes the hardware architecture of the flight payload and the ground nodes that are strategically distributed across the designated area of interest.

A. Payload

In the 2023 NASA Ames Flight Campaign, the designated aerial vehicle was the Freefly AltaX Gen2.1 platform, with flight dynamics governed by the Pixhawk flight controller. The flight payload, essential for comprehensive flight state assessment, encompasses a CPU, a power supply unit, a display interface, and an assortment of advanced sensors. These sensors include a dual Visual-IR camera, Lidar, an Inertial Measurement Unit (IMU), and a radio frequency (RF) Mesh modem for streamlined communication.

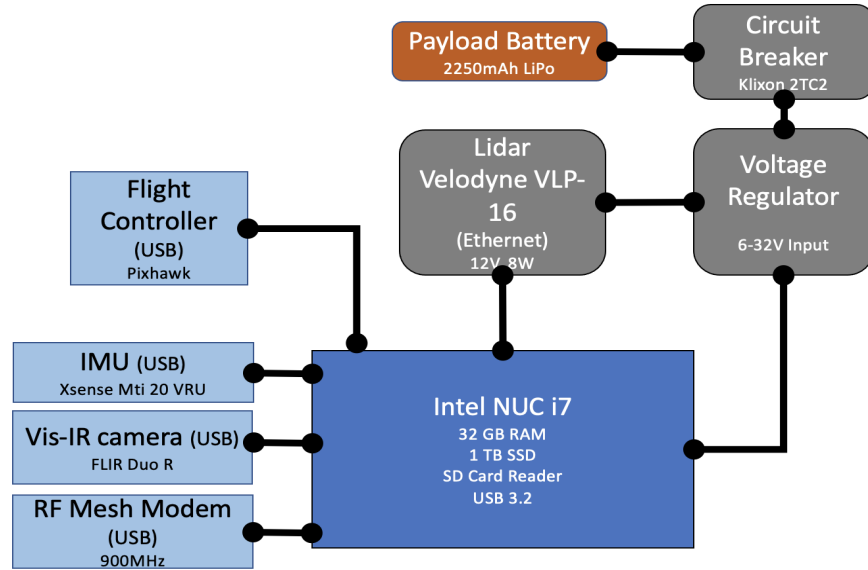


Fig. 1 Payload Block Diagram

The schematic representation in Figure 1 elucidates the intricate composition of the payload, featuring the FLIR DUO-R Thermal Infrared (IR) and 4K Visual Camera, Xsens MTI-20 VRU IMU, Intel NUC i7 as the CPU unit, a portable battery source, and the Velodyne Lidar Puck VLP-16. It is noteworthy that the payload’s battery is intricately connected to the Intel NUC and Lidar components through a voltage regulator and circuit breaker mechanism, mitigating the risk of voltage surges that could compromise the integrity of the sensor circuitry.

Figure 2 provides a visual overview of the Freefly AltaX flight configuration with the integrated payload. The

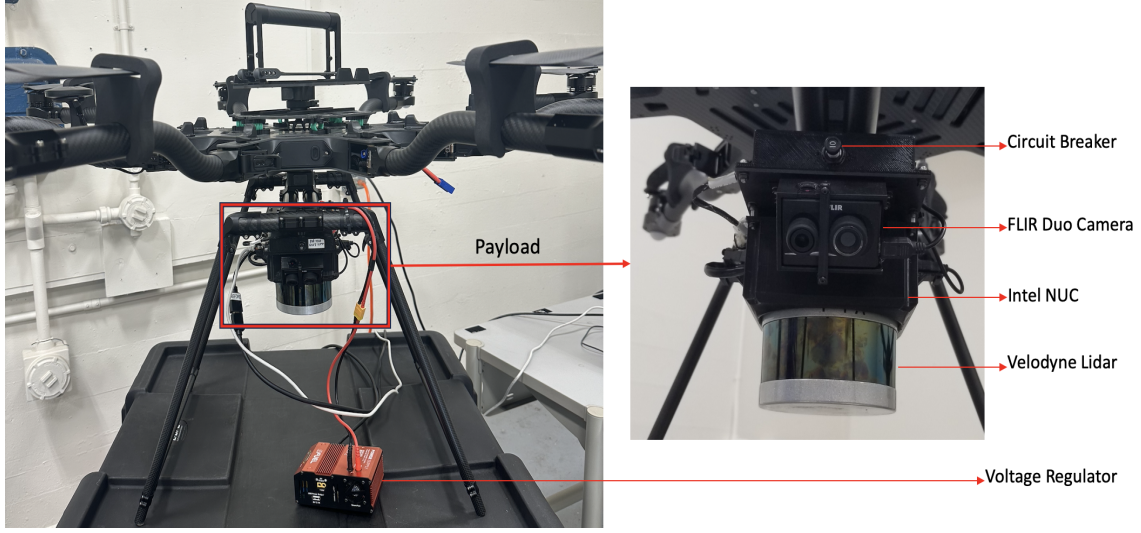


Fig. 2 Freefly AltaX with the Payload

smaller inset on the right provides a detailed close-up view, highlighting the comprehensive sensor suite utilized for scientific data collection throughout the campaign.

B. Ground Node

Ground nodes constitute pivotal sensor stations strategically positioned on the ground to meticulously estimate and document flight activities, thereby facilitating comprehensive surveillance. For the explicit purpose of implementing distributed sensing algorithms, two distinct ground node architectures are presently employed.

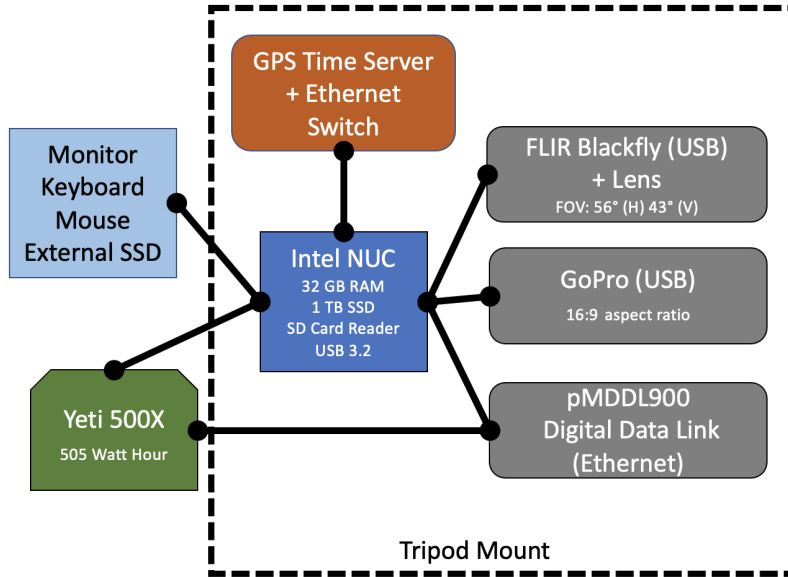


Fig. 3 Block Diagram of the Camera Ground Node

In the envisaged camera ground node structure, elucidated in Figure 3, a sophisticated configuration is realized, comprising a central processing unit (CPU), an array of sensors, and a RF modem designed for communication. This configuration closely mirrors the architecture observed in the airborne payload. The comprehensive ensemble includes FLIR Blackfly S visual and GoPro Hero 10 Black cameras, Velodyne Lidar Puck VLP-16, Intel NUC i7 as the CPU

unit, and the MicroHard pMDDL900 Digital Data Link serving as the communication modem. The modem establish connectivity with the Intel NUC through ethernet links, ensuring seamless data transmission. It is noteworthy that the Intel NUC necessitates auxiliary components such as a monitor, keyboard, mouse, and an external SSD for operational accessibility. The entirety of the detailed setup, represented by dotted lines in Figure 3, is securely mounted on a tripod for stability and precise positioning during operational deployment.

Ongoing integration efforts involve the inclusion of FLIR Boson 320 IR camera and the MicaDense RedEdge-MX multispectral camera, seamlessly interfaced with the Intel NUC through USB ports, in conjunction with the Lidar and other cameras.



Fig. 4 Bench Setup of Camera Ground Node



Fig. 5 Camera Ground Node at the Sensor Station

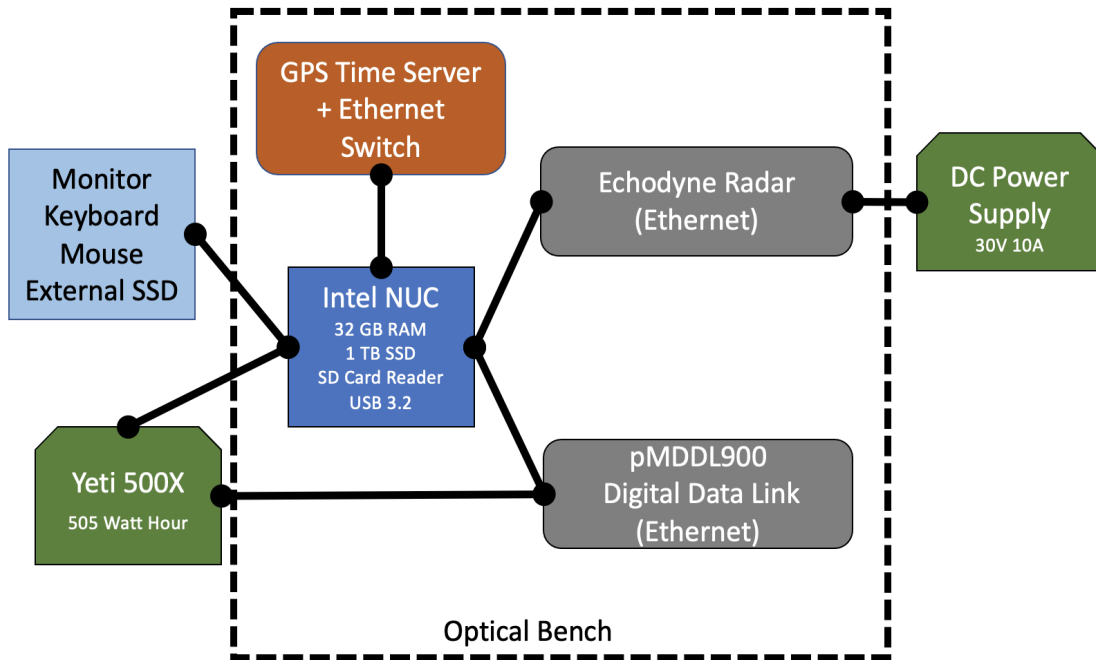


Fig. 6 Block Diagram of the Radar Ground Node

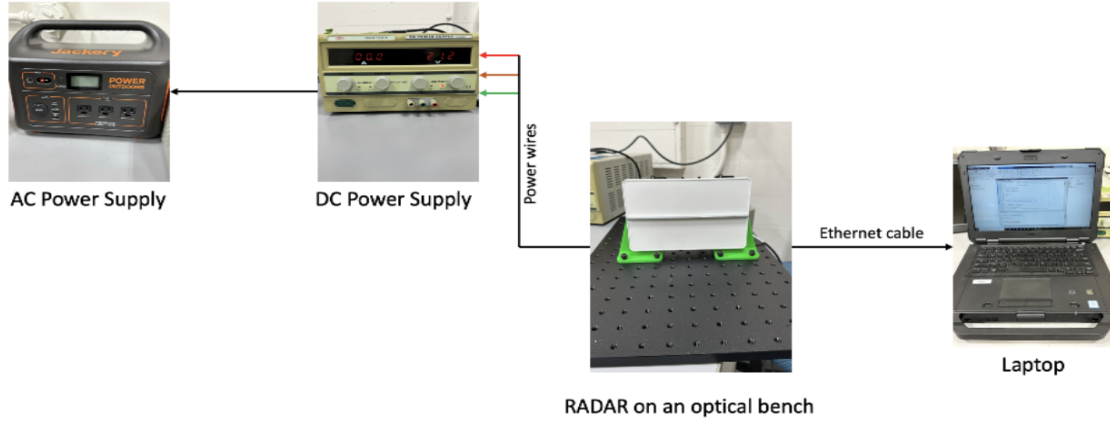


Fig. 7 Block Diagram Showing the Radar Connections

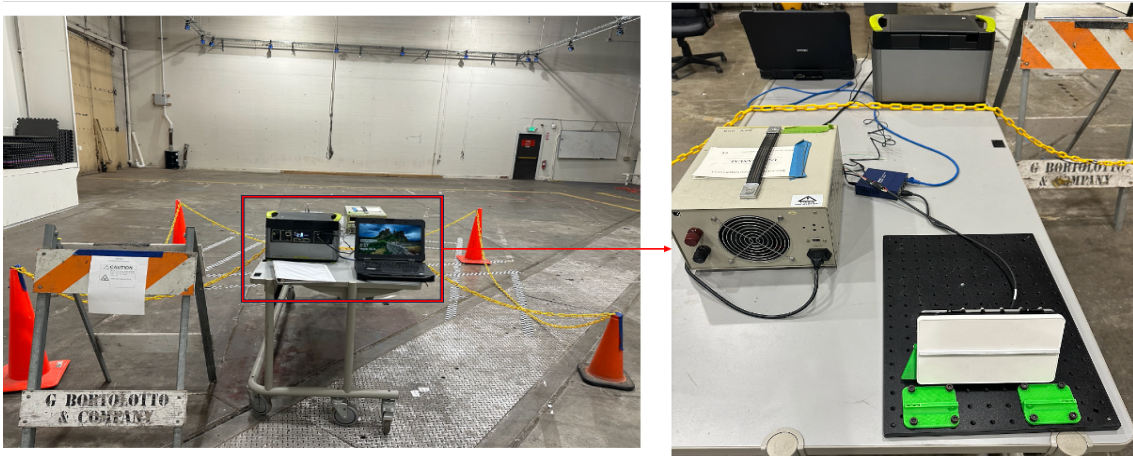


Fig. 8 Bench Setup of Radar Ground Node

Figure 4 illustrates the sensor suite meticulously positioned on a tripod within a laboratory bench setup along with the touch screen monitor and a portable power supply, while Figure 5 shows the ground node setup during a flight test.

On the other hand, the radar ground node structure, depicted in Figure 6, replicates the mentioned components but differs in its use of a radar unit (instead of the camera unit), specifically the Echodyne Echoflight radar. Notably, the radar unit is independently powered by a DC power supply and interfaces with the NUC via an ethernet link, concurrently connected to the communication modem through an ethernet switch. Presently, the acquisition of more advanced accessories for the radar setup is in progress, acknowledging the substantial nature of the existing configuration, which may pose logistical challenges during outdoor flight testing. Hence, Figure 6 is to be regarded as a representation of a more sophisticated block diagram of the current setup. A closer inspection of the actual radar connections is provided in Figure 7, demonstrating the interconnection of each hardware component. In the context of the DC power supply connection, it is imperative to note that the distinct color codes of the wires signify specific polarities: red corresponds to the positive terminal, maroon to the negative terminal, and green to the ground.

Figure 8 depicts the laboratory bench configuration of the radar ground node, captured during an indoor flight test experiment. Evidently, requisite safety measures, such as the implementation of safety cones, chains, and warning boards, are observed meticulously during the testing phase or whenever the radar is activated.

It is important to note that an essential caveat pertains to the presence of substantial metal framing within the confines of the indoor test site, potentially causing interference with the radar functionality. Consequently, optimal radar performance may be impeded under these conditions.

Figure 9 presents the configuration of multiple ground nodes of different types distributed throughout the system.

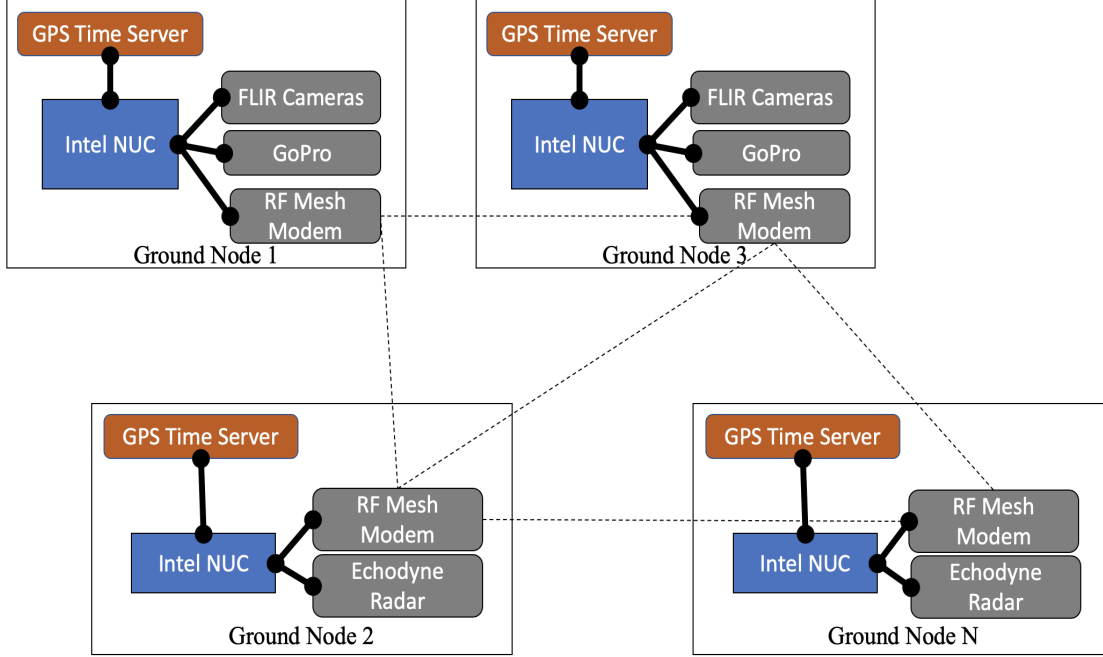


Fig. 9 Multiple Ground Nodes

As previously indicated, the interconnection is not physical, relying instead on a radio frequency of 900 MHz for signal transmission. Observably, not all nodes are mutually connected, and this lack of continuity may arise from factors such as inter-node distances, signal impediments like trees or buildings, or other pertinent considerations. Thus, constructing a system with closely packed nodes is impractical. Consequently, a communication system has been adopted to facilitate inter-node communication without the necessity for direct connections between each node, enabling seamless contact between all nodes. This communication system architecture is discussed in section IV.

III. Sensor Description

This section will provide comprehensive details regarding each sensor, encompassing its hardware specifications, technical characteristics, and rationale for its selection or consideration.

A. FLIR Blackfly S Visual Camera

The camera's color transformation tools provide clean, high-resolution images while also supporting an onboard operating system, which demonstrates portability. Furthermore, the polarization and the Back-Illuminated sensor collectively contribute to the production of precisely desired images. The camera seamlessly integrates continuous single-frame and multi-frame acquisition modes, providing versatility in addressing various imaging needs. The broad exposure range, spanning from 4 microseconds to 30 seconds, coupled with the CMOS sensor's adjustable shutter speed, contributes to its advanced imaging capabilities. Additionally, the inclusion of a 6 MB non-volatile flash memory guarantees dependable data retention, particularly crucial for surveillance applications. Its power-efficient operation, consuming a mere 3 watts, along with compact dimensions (29 mm × 29 mm × 30 mm), positions the camera as an ideal choice for aerospace applications, where size and power constraints are paramount considerations. Table 1 provides a comprehensive overview of the camera's technical specifications, emphasizing its suitability for specialized applications [5]. Figure 10 visually represents the camera, providing a glimpse of its design and form factor.

B. FLIR Boson 320 Thermal IR Camera

The FLIR Boson serves as a long-wave infrared (IR) thermal camera module, employing an IR video processing architecture to facilitate sophisticated image processing and standard communication interfaces, all within a framework



Fig. 10 FLIR Blackfly S



Fig. 11 FLIR Boson 320

Resolution	720 × 540
Frame Rate	522
Megapixels	0.4
Pixel Size	6.9
Analog to Digital Converter	8-bit, 10-bit, 12-bit
Acquisition Modes	Continuous Single Frame & Multi Frame
Exposure Range	4 μs to 30 seconds
Flash Memory	6 MB non-volatile memory
Frame Rate	522
Power Consumption	3 W
Dimensions [W x H x L]	29 mm × 29 mm × 30 mm
Operating Temperature	0° to 50°C
Sensor	Sony IMX287, CMOS
Sensor Format	1/2.9"
Readout Method	Global shutter

Table 1 FLIR Blackfly S Specifications Table

that prioritizes low power consumption. Its advanced embedded and video processing capabilities extend to seamless integration with auxiliary sensors, such as third-party cameras, GPS, and Inertial Measurement Units (IMUs) [6]. The sensor's specifications, outlined in Table 2, provide a comprehensive overview of its technical attributes, while Fig. 11 visually represents the Boson IR camera.

Resolution	320 x 256
hFoV	6.1°
Focal Length	36 mm
Dimensions	21 x 21 x 11 mm
Weight	7.5 grams
Power consumption	500 mW
Temperature range	-40 °C to +80 °C

Table 2 FLIR Boson 320 Specifications Table

C. FLIR Duo-R Thermal IR and Visual camera

The FLIR camera sensor functions as a dual thermal and video imaging system, consolidating both capabilities within a singular component [7]. Its operational features encompass the provision of precise GPS, temperature, and altitude data for each captured image, facilitated by an onboard GPS receiver, temperature, humidity, and altitude sensors. Seamless integration with MAVLink-compatible flight controllers enhances the camera's compatibility and utility in aerial applications. The sensor further incorporates MSX blending to enhance image detailing in broad daylight conditions, along with the ability to facilitate live analog/digital video streaming. Predominantly utilized in the payload, the critical specifications of the sensor are detailed in Table 3, while Fig. 12 visually represents the camera.



Fig. 12 FLIR Duo-R camera



Fig. 13 Velodyne Puck

Dimensions	85 x 81.3 x 65.5mm
Thermal Lens	9 mm: 35° x 27°
Thermal Frame Rate	9 Hz
Weight	325 g
Digital Video Output	1080p60, 1080p30, 720p60
Temperature Range	-20°C to +50°C
Operational Altitude	+38,000 feet
Power Dissipation	10 W
Visible Camera FOV	56° x 45°
Visible Sensor Resolution	4000 x 3000
Thermal Sensor Resolution	336 x 256
Input Voltage	5.0 VDC

Table 3 FLIR DUO Specifications Table

D. Lidar - Velodyne Puck VLP-16

The VLP-16 employs sixteen infrared (IR) lasers in tandem with IR detectors to gauge distances to objects. Each IR laser records the emission time and direction when releasing a laser pulse. The pulse traverses through the air until encountering an obstacle, which reflects a portion of the energy. Paired IR detectors capture this reflected energy, noting the acquisition time and power. Housed securely within a compact, weather-resistant enclosure, the array of laser/detector pairs undergoes rapid rotation within its fixed housing to conduct a comprehensive scan of the surrounding environment. Firing each laser approximately 18,000 times per second generates a substantial dataset of 3D point data in real-time. Combining the sixteen laser/detector pairs into a single sensor and pulsing each at 18.08 kHz allows for

measurements of up to 300,000 data points per second [8]. Velodyne extends its offerings with VeloView, a live sensor data viewing and saving platform. The VLP-16 sensor supports a dual return mode, enhancing accuracy in capturing details of intricate environments featuring scattered small objects and non-opaque surfaces. Notably, the dual return mode provides users with multiple returns, augmenting the usability of points [9]. This versatile sensor finds application in both the payload and ground nodes.

E. Microhard pMDDL900 Digital Data Link

The digital data link constitutes a 2x2 (dual antennas) Multiple Input Multiple Output (MIMO) 900 MHz wireless Original Equipment Manufacturer (OEM) solution [10]. This solution concurrently facilitates ethernet, serial, and USB communications, enabling the seamless transfer of video and metadata. Employing Maximal Ratio Combining, Low-Density Parity Check, and Maximal Likelihood decoding techniques ensures robust RF performance. Operational versatility is evident as it can function in Point-to-Point (Master-Slave), Point-to-Multipoint (Master-multiple slave), and Mesh Network configurations, thus presenting Master, Remote, and Relay modes. The OEM unit itself weighs approximately 7 g, while the enclosed system has a weight of around 230g [11]. Security is of paramount importance in surveillance applications, and it is ensured through the implementation of 128-bit Advanced Encryption Standard encryption. The inclusion of Serial and USB Ports, coupled with dual Ethernet Ports for both Local Area Network and Wide Area Network connections, enhances its adaptability and functionality.

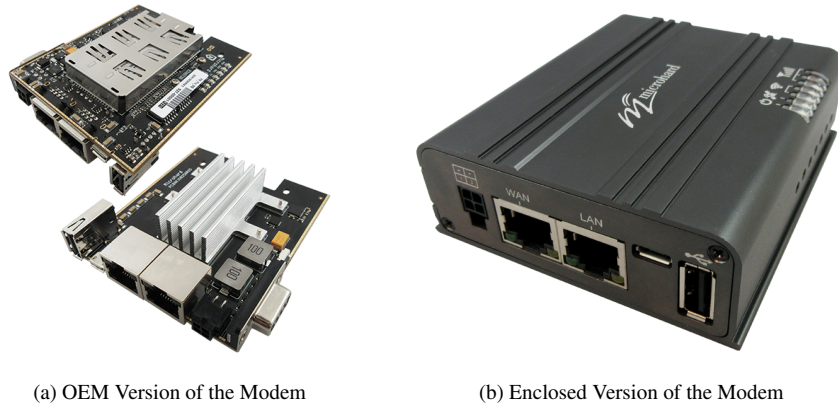


Fig. 14 Microhard pMDDL900

F. Intel NUC i7

The CPU unit employed in both the ground node and payload is the Intel NUC, featuring an Intel Core i7-1165G7 Processor, as detailed in [12]. Responsible for data storage and processing, the Intel NUC facilitates both offline and real-time processing based on specific requirements. All NUCs within the laboratory are currently configured to run Windows 11 but can be booted with any operating system as needed. With specifications including 8GB DDR4-3200 RAM, a 500GB Gen4 NVMe SSD, and an Intel graphics card, the Intel NUC ensures efficient and capable performance. Additionally, it offers 5 USB ports, an Ethernet port, an HDMI port, and a microphone port for versatile connectivity. The enclosed unit exhibits dimensions of 117 x 112 x 56mm, as illustrated in Fig. 15.

G. Jackery Portable Power Station Explorer 500

The design of the portable power station, as detailed in [13], incorporates a lithium-ion battery pack optimized for maximum power utilization. With a substantial 500-watt-hour power capacity, this portable power station weighs a mere 13.3 pounds and boasts dimensions of 11.84 x 7.59 x 9.2 inches, rendering it highly compact and easily transportable, aided by a convenient handle. Equipped for versatility, it features 1 AC outlet, 3 USB slots, and 2 DC ports, as depicted in Fig. 16. Furthermore, the power station is rechargeable, eliminating the need for fuel.



Fig. 15 Intel NUC 11th generation



Fig. 16 Portable Power Supply

H. Echodyne Echoflight Radar

Echodyne's MESA (Metamaterial Electronically Scanning Array) simplifies radar systems, offering advantages over traditional alternatives. EchoFlight, utilizing MESA technology, serves as a scanning array radar designed for small to medium UAS collision avoidance. The true electronically scanning beam radar provides active Search While Track (SWT), intelligent beam allocation with i-SCAN, improved clutter suppression, IMU-based self-stabilization, all-electronic architecture, and dynamically reconfigurable field of regard, addressing critical requirements for safe and effective airspace management.

MESA radars operate at 24.55 GHz with a transmit power under 4 watts, following FCC guidelines for Maximum Permissible Exposure (MPE) [14]. Despite similarities to low-power radios, the focused radar beam poses a slightly higher risk. With a nominal gain of 21 dBi (22 dBi max), the effective radiated power is amplified, necessitating a conservative safe operating distance. Echodyne adheres to FCC OET Bulletin 65 [15], using principles akin to marine radar manufacturers for safe operational distances. Operators must comply with FCC Requirements for Radio Frequency Exposure, maintaining a distance greater than 1 meter from the radar's axis over the 120 degrees azimuth and 80 degrees elevation scanning field. Transmitting is prohibited within the MPE radius to prevent exceeding FCC-set exposure limits. As a safety precaution during testing, chains and cones are placed around the radar at the recommended safe distance to prevent entry into the exposed zone, including by the operator. A warning sign is positioned at the zone's entrance, providing information about radiation exposure. The setup ensures that operators can safely operate the radar from outside this zone.



Fig. 17 Echoflight Radar



Fig. 18 MicaSense Multispectral Camera

I. MicaSense RedEdge-MX Multispectral Camera

The MicaSense RedEdge-MX stands out as a robust and durable multispectral sensor designed for professional applications in agricultural and vegetation management drone mapping. This sensor is equipped to capture data across five distinct spectral bands [16], rendering it one of the most versatile solutions currently available. The inclusion of features such as optimized Ground Sampling Distance, the advanced DLS 2 light sensor, and the capability to generate plant health indexes and RGB (color) images in a single flight underscores its adaptability and functionality. Its advanced sensor technology ensures the acquisition of high-quality and precise data whenever required.

The multispectral camera as shown in Figure 18, characterized by its outstanding features, provides invaluable data and insight for aerial applications. It adeptly captures data across five narrow spectral bands during flight, offering a comprehensive perspective of the surveyed environment. Notably, the camera achieves an impressive image resolution, providing clear details at a resolution of 8 cm/pixel from an elevation of 400 ft (120 m). The convenience of data management is evident as all captured images, complete with geotags, are efficiently stored on a single SD card. Its standalone operation, coupled with the option for an external trigger and the capacity to integrate data from the host aircraft, enhances flexibility and adaptability. Users can easily configure settings through a user-friendly web-based page accessible from any Wi-Fi-capable device. Further promoting ease of use, the camera incorporates embedded mounting points, simplifying the integration process. The presence of global shutter imagers eliminates the need for a gimbal, contributing to its overall stability and versatility in various aerial scenarios.

IV. Communication Framework

Establishing a distributed sensing framework poses a principal challenge in the form of implementing a resilient communication system capable of transmitting sensor data seamlessly throughout the network, minimizing both loss and latency. This imperative not only addresses the efficiency of data transmission but also ensures the safety and accuracy of the entire system. As elucidated in preceding sections, individually connecting each modem for comprehensive connectivity is deemed impractical. Consequently, a mesh architecture is judiciously adopted to surmount these challenges, fostering a more robust and interconnected system.

A. Mesh Architecture

A mesh network comprises a collective assembly of connectivity devices functioning as a unified network, presenting numerous sources of connectivity within the designated area of interest, as opposed to relying on a singular route. The inherent broadcasting mechanism of mesh networks diverges from traditional single-location broadcasts, enabling superior coverage across expansive spaces. The interconnected points within the mesh network establish wireless connections with each other, fostering communication without the need for a centralized location. This feature ensures rapid and efficient data routing, emphasizing the advantageous capabilities of mesh networks in terms of coverage and connectivity. Figure 19 serves as a schematic illustration of RF Modems within a Mesh network. The diagram features a block symbolizing the flight, housing an embedded RF modem. Orange lines show connections between the flight and ground nodes, while blue lines signify connections among the ground nodes. Notably, the figure reveals that the flight is within range of only a subset of ground stations, attributed to factors such as distance or other considerations.

The employed mesh architecture empowers the system to relay flight information to all nodes by implementing node-to-node rerouting. Essentially, the mesh network demonstrates notable efficacy in rerouting capabilities, rendering it a self-healing architecture. The mesh network ensures an adaptive framework for the inherently dynamic behavior from the aircraft, which demonstrates adaptability for large fluctuations within the system. Hence, for extensive regions, strategically situating a chosen subset of modems at specific locations can effectively provide comprehensive coverage for the entire designated area. This emphasizes the efficiency and versatility of the mesh architecture in enhancing network coverage optimization.

In Figure 20, the block diagram provides a comprehensive overview of the integrated distributed sensing framework. The depicted blocks offer a simplified representation of both the airborne payload and ground nodes, strategically tailored to accommodate the spatial constraints of the illustration. This schematic captures the intricate interplay between these components, effectively conveying the essence of the distributed sensing paradigm. The intentional visual abstraction ensures a streamlined presentation of core elements, maintaining clarity and coherence in the diagrammatic representation.

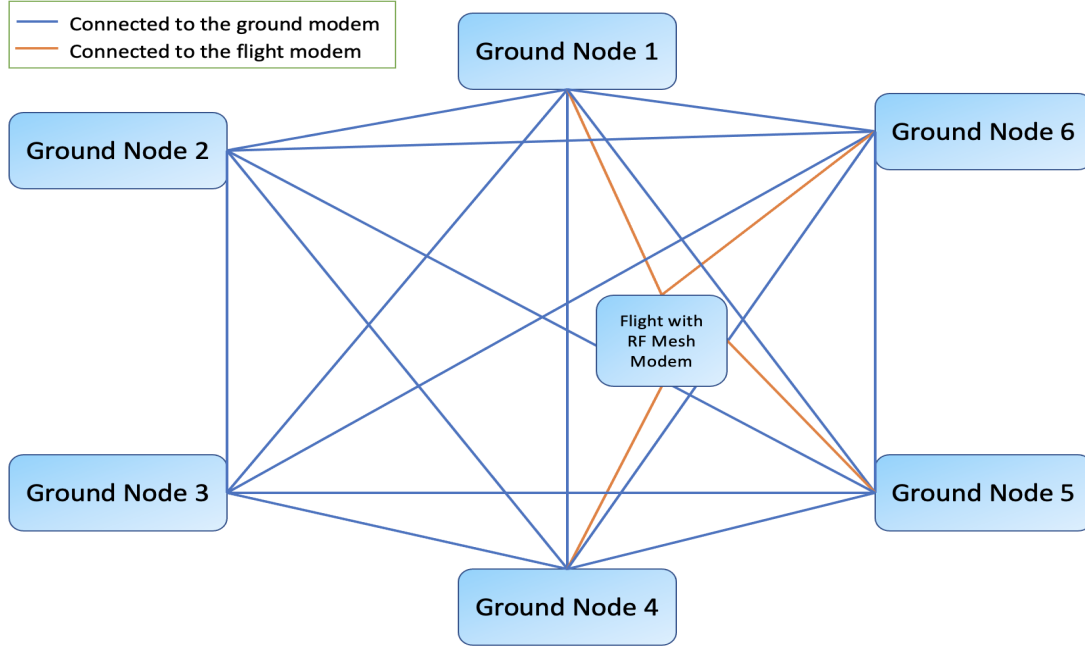


Fig. 19 Mesh Configuration of the Modems

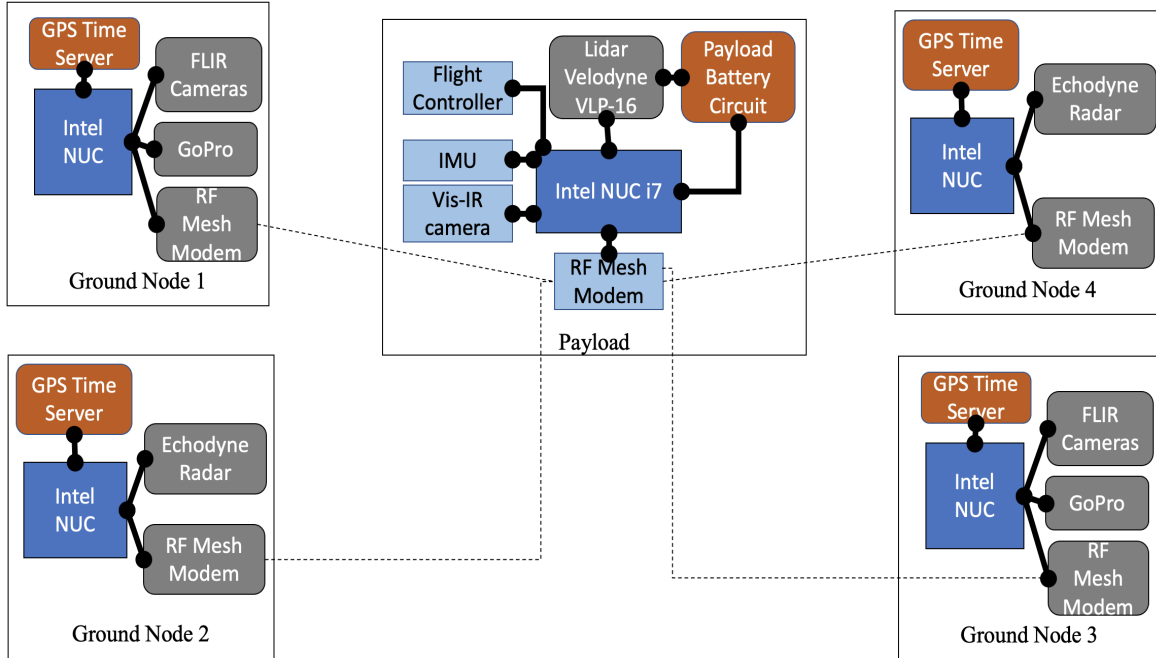


Fig. 20 Overall Block Diagram of the Sensor Station Setup with RF Communication

B. Modem Configuration

Table 4 outlines the configurations essential for the establishment of the modem in a mesh network. Operating within the 900 MHz radio frequency band, these modems exhibit an 8 MHz channel bandwidth, while their transmit power is meticulously calibrated to 20 dBm, ensuring the efficacy of signal transmission. The specified 900 MHz channel, spanning from 15 to 917 MHz, affords a broad spectrum conducive to wireless communication across varied

frequencies. Demonstrating a noteworthy wireless distance capability of 3000 meters, these modems excel in facilitating extended-range communication scenarios.

Configured in the Mesh operation mode, all modems sharing a common Mesh ID collaboratively form a cohesive mesh network, enhancing network resilience and interconnectivity. The encryption protocol employed for securing communications is AES-128, underscoring a commitment to robust data protection within the mesh architecture.

Fundamental settings for the modems encompass the Mesh ID and encryption type. Modems with identical Mesh IDs become integral constituents of the mesh network. Additionally, each modem assumes a static IP address, with Dynamic Host Configuration Protocol disabled to prevent IP address repetition, an imperative to maintain network integrity.

Following the setup of the mesh network, the web interface provides a detailed overview, listing connected modems, their Received Signal Strength Indicator (RSSI), and other pertinent details. Further information regarding the web interface functionalities can be found in the Microhard user manual [17].

RF Band	900 MHz
Channel Bandwidth	8 MHz
Tx Power	20 dbm
900MHz Channel	15-917 MHz
Wireless Distance	3000 m
Operation Mode	Mesh
Encryption type	AES-128

Table 4 Parameters for Modem Mesh Configuration

V. Software Architecture

The general operational phases of the software framework are shown in Figure 21 below. This model guides the framework through various operating modes supporting the surveillance use case. When a potential target is identified in one or more sensors, the acquisition phase identifies the target as an entity to be estimated and confirms the target. The initial topology determination phase specifies an initial distributed sensing network topology over various elements in the airspace that meets the requirements and estimation goals while satisfying constraints. Once the topology has been established, the system enters a nominal operational mode. During nominal operation, the target state estimate is updated at each time-step based on updates from the sensors. Asynchronously, the framework performs three other functions. The framework monitors the current network topology to identify any event that would require a topology change, such as the target vehicle leaving a sensor volume, loss communication from a sensor, etc. Additionally, the framework provides continual quality estimation across all sensors with overlapping observation of the target through cross-validation of each sensor with the consensus. While the target is estimated in the specified estimation network topology, the system will perform target classification to help classify the target for the consumers of the estimate. For instance, determining if the target is a sUAS, an eVTOL, a helicopter, or a bird will be useful information for airspace operators and for onboard detect-and-avoid functions. The functional modes of operations in Figure 21 represent the major ‘Level 1’ operational modes and Figure 22 show the ‘Level 2’ acquisition modes. Additional details of the framework can be found in [18].

For this initial experiment, the prototype software system was built using NASA’s Reflection Architecture for real-time systems [4][19], with software modules built in C/C++, and parts of the estimation filter module ported from Matlab. The major services developed for this test are shown in Figure 23. Hardware interface modules for the GPS receiver, hardware modems, and cameras are responsible for handling software to hardware communication over the hardware-specific connection. The camera modules for instance are responsible for capturing and decoding images in real-time from the hardware sources. The modem module is responsible for extending the Reflection Architecture’s communication system across the network to other instances of the airborne and ground-based networks. Data logging services are responsible for storing data to a file system, which was utilized in post-processing for analyzing performance of these experiments. Image processing and object tracking services are responsible for processing the images in real-time to detect and track airborne objects in the field of view of the sensors. RF localization services are responsible for determining position of the mesh modems in the network utilizing RF information from the mesh modems.

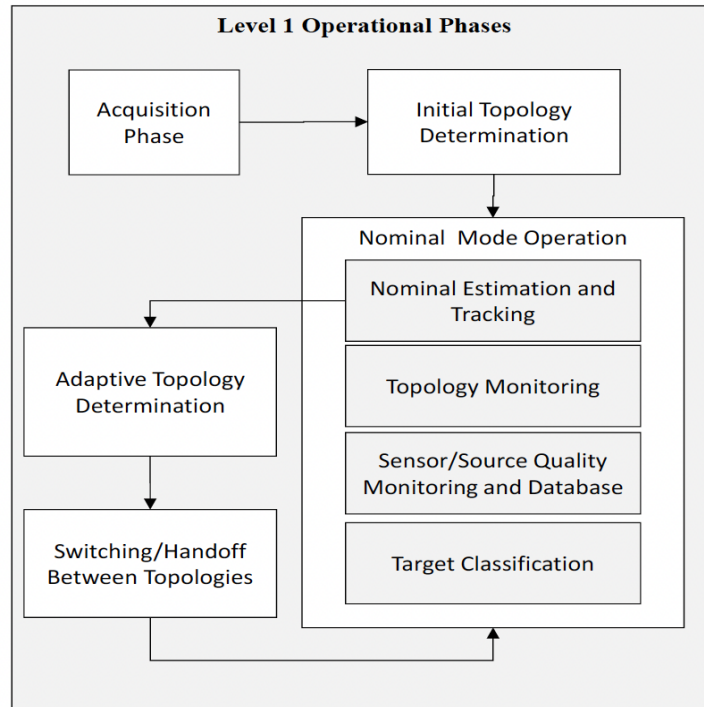


Fig. 21 Operational Model for a General Framework for Distributed Sensing

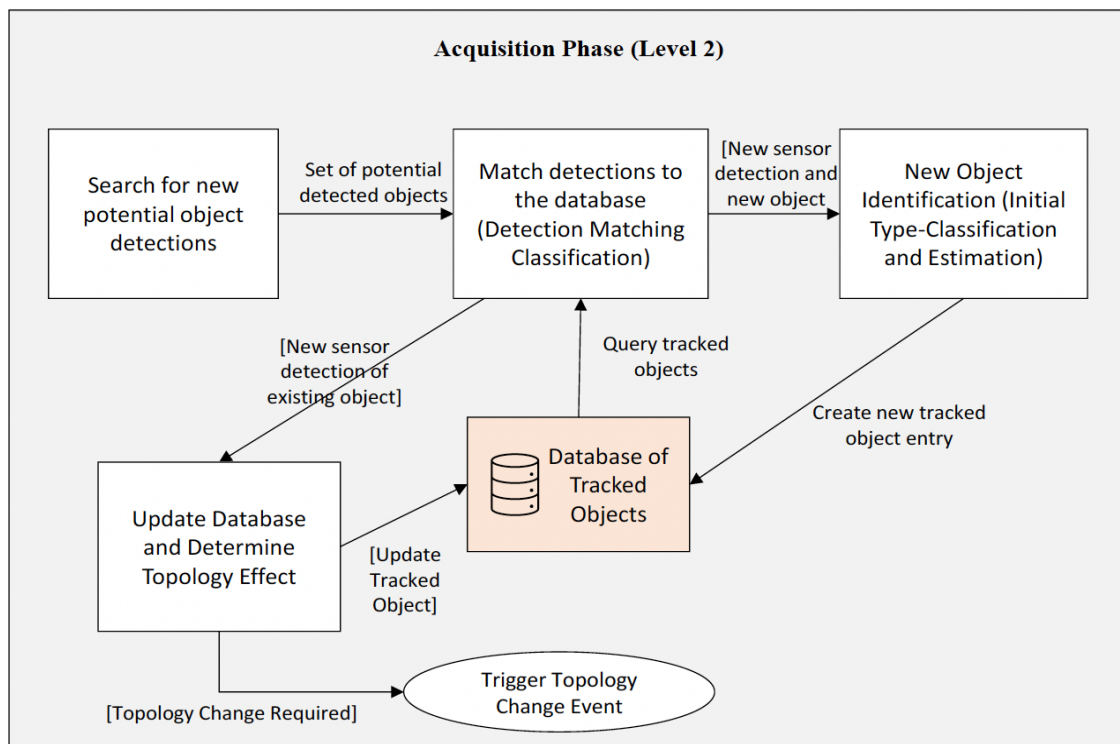


Fig. 22 Acquisition Model for a General Framework for Distributed Sensing

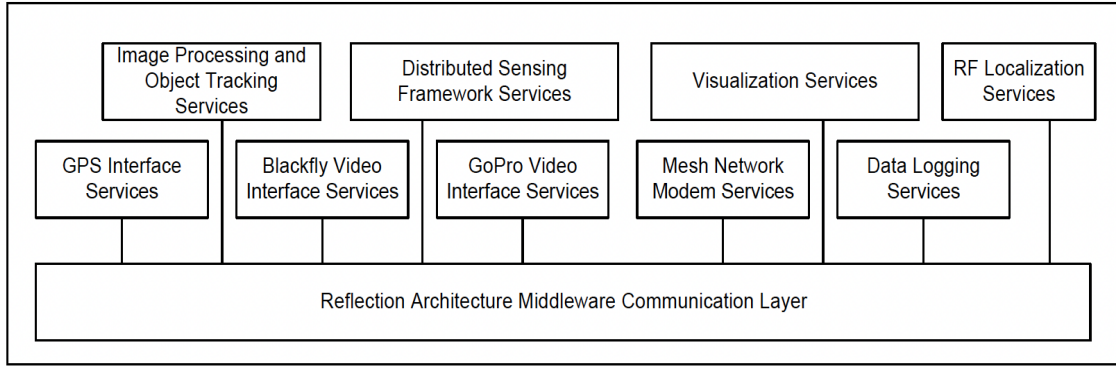


Fig. 23 Major Services and Software Modules for the Distributed Sensing Flight Experiments

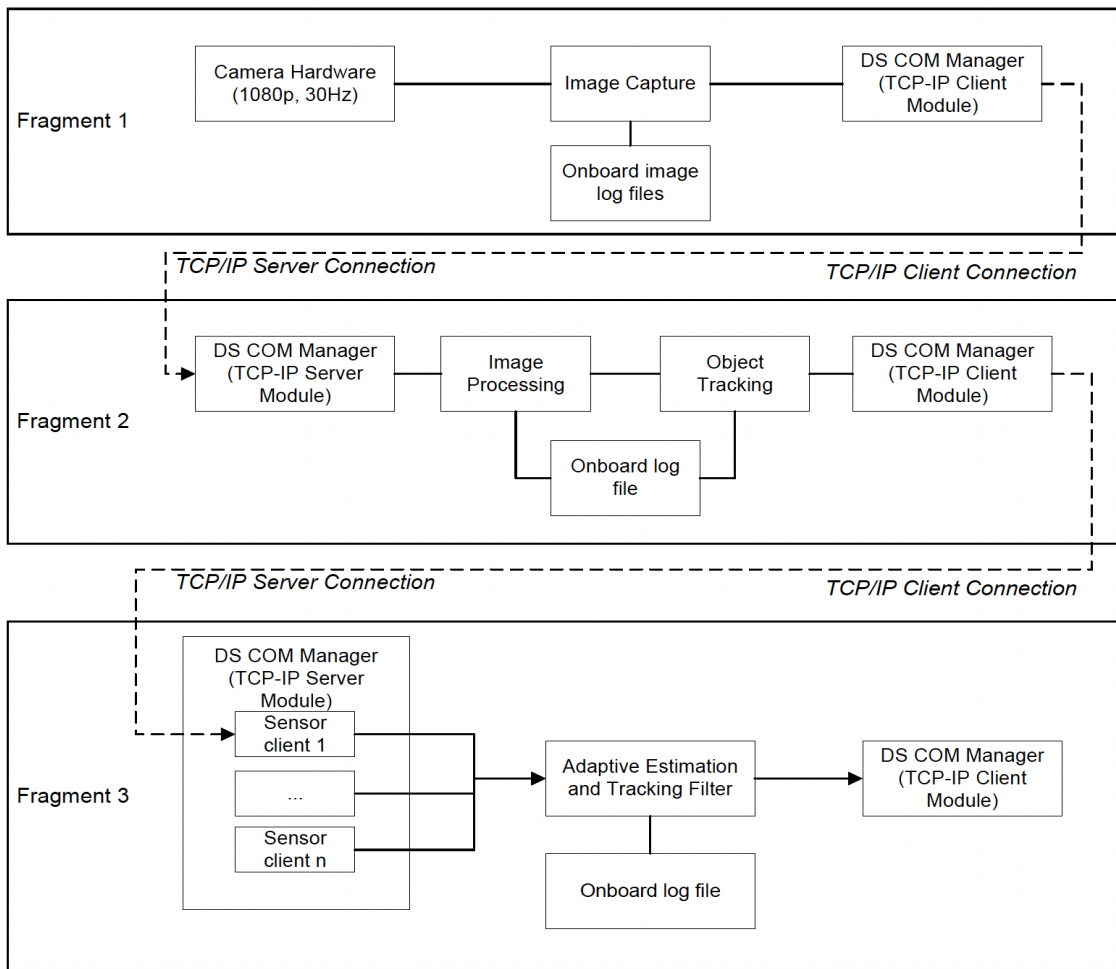


Fig. 24 Implementation of Components in TCP/IP Client Server Fragments (Pre-Assembly)

The Distributed Sensing framework needs the ability to provide an adaptive network for operation that will require constant reconfiguration and restructuring of the network topology. Towards these self-assembling goals, each component of the sensor processing pipeline was developed into “fragments” as shown in Figure 24. Each fragment can be executed as a standalone application with client and/or server capabilities for inter-fragment communication. This allows each fragment to be assembled and easily re-assembled in real-time in response to the requirements and constraints the

system is currently encountering. The top fragment shows encapsulation of the camera hardware interfaces, which is responsible for capturing images and communicating them to the next fragment. The second fragment shows the image processing and object tracking pipeline components. In this initial experiment implementation, these components operate on a per-sensor basis without additional information from other sensors. This fragment sends detection and tracking information to the other fragments. The adaptive estimation and tracking filter handles the calculations for estimation of targets, which have been identified through correlation and matching of signals across the sensor network. This fragment's server allows multiple clients to connect based on which sensors contain information that is relevant for the filter. In this initial experiment's implementation, calibration and registration of sensors were performed offline in the pre-process, with future plans for implementing self-calibrating functionality. For details on self-calibration and sensor registration, see [20]. For details on the distributed correlation and matching problem, see [21]. For details on the image processing and tracking pipeline, see [22]. For details on the adaptive estimation and tracking filter, see [23].

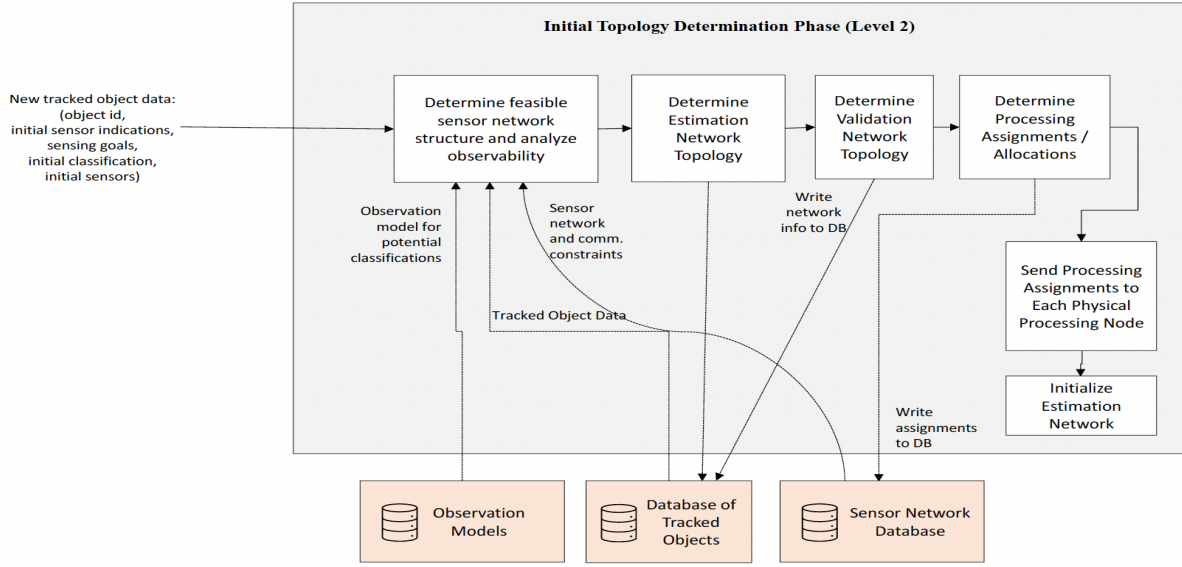


Fig. 25 Topology Determination Phase

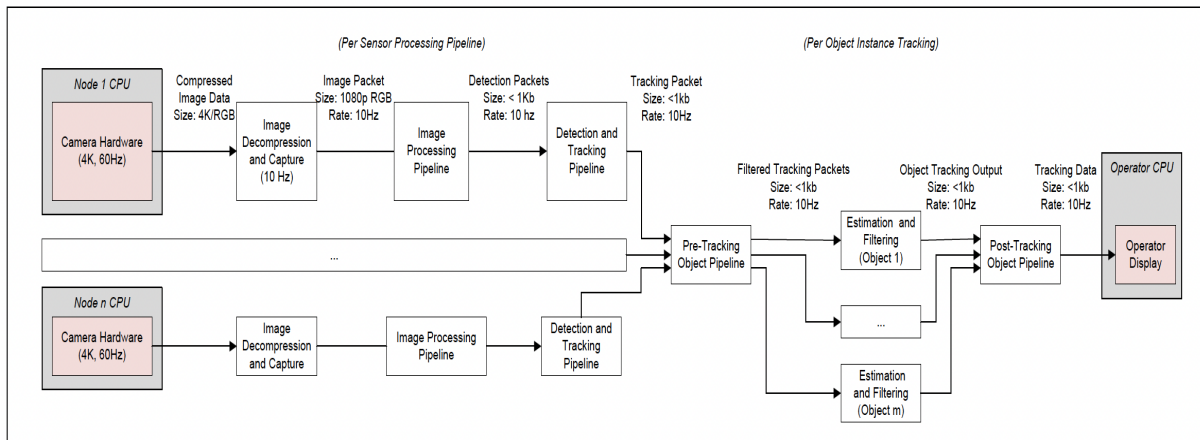


Fig. 26 Distributed Vision-Based Estimation System Assembly Goal (Pre-Assignment)

A. Assembly and Assignment Problem

During real-time operation, the topology determination system module is responsible for solving the assembly problem. Given the destination node, hardware available, and current sensor state, the system must determine the end-to-end topology that meets the requirements for estimation. The major software requirements for assembly and assignment are shown in the requirements drawing in Figure 25 below.

For these initial flight test experiments, the vision-based tracking sub-system assembly is shown in Figure 26. Between each fragment are communication requirements that include bandwidth and latency constraints. These are passed along to the processing assignment/allocation system that is responsible for allocating software to specific nodes in the system, as outlined in the software requirements (Figure 25).

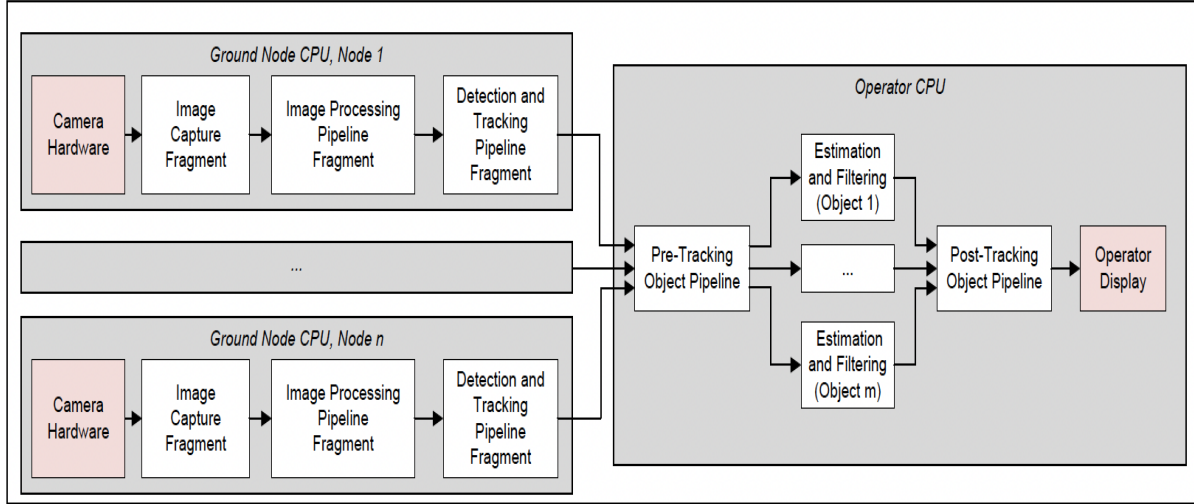


Fig. 27 Assembled Vision-Based-Tracking System Component with Hardware Assignments

The specific approach being developed for fragment-to-hardware allocation and assignment are detailed in [24]. For initial evaluation in this first set of flight tests, the specific assignments were hard-coded into the assignment/processing module. Future development and experiments of this prototype system will bring in the assignment algorithms as these components mature. The hard-coded assignments are shown in Figure 27. The per-sensor processing pipelines were allocated to the ground node CPU to avoid high-bandwidth usage of the network. The framework components and estimation were assigned to the ground operator's CPU, which is also responsible for displaying results to the operator in real-time. Note that from these experiments, the research team determined that additional processing and relay nodes would provide better real-time results, so in future experiments, the framework and per-object filtering network fragments would likely be reassigned from the operator's CPU to separate dedicated relay CPU.

VI. Test Setups

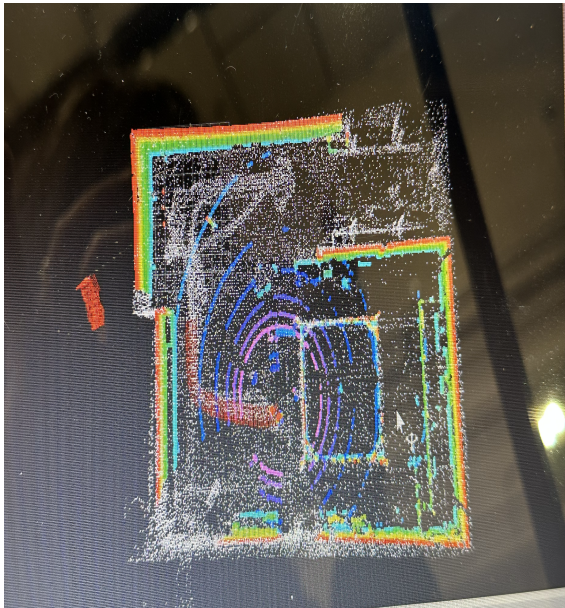
A. Lidar Walk-Around Test

The Lidar walk-around test serves as a pivotal exploration to assess the feasibility of utilizing Lidar data exclusively for localization purposes. Consequently, Lidar localization constitutes the initial series of tests within the indoor experimental framework involving the payload. The inaugural walk-around test entails a drone storage black box affixed with wheels, accommodating the entire payload ensemble along with a monitor, keyboard, and mouse positioned on the top surface as shown in Figure 28. The black box is systematically maneuvered in a predetermined pattern to accrue Lidar data. The Lidar Simultaneous Localization and Mapping (SLAM), specifically Lidar Odometry and Mapping in Real-time (LOAM) [25], is executed to facilitate Lidar localization.

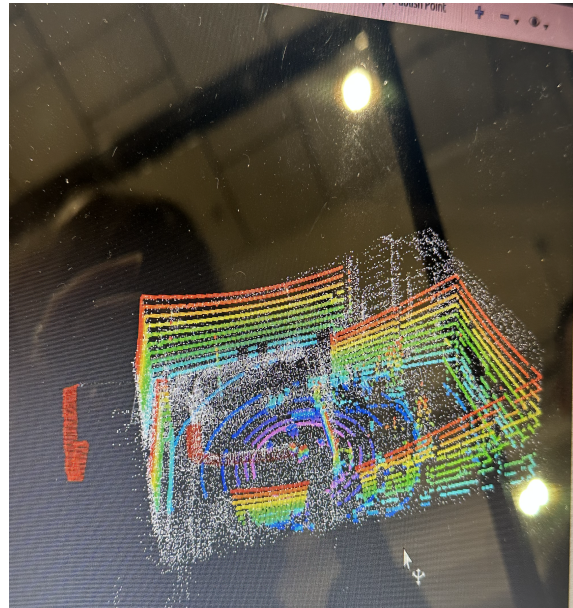
Figure 29 shows the snapshots of the LOAM output screen during the testing phase. These visual representations vividly portray the indoor arena, providing detailed interior perspectives. To enhance the robustness of the Lidar localization, the same test protocol was reiterated with ground nodes strategically installed across the entire area. This iterative process was designed to obtain supplementary validation from the ground sensors, fortifying the reliability of



Fig. 28 Walk-Around Setup of the Payload



(a)



(b)

Fig. 29 Lidar Output as seen on the Display Screen

the Lidar localization outcomes.

B. RF Mesh Modem Drive-Around Test

In May-June 2023, a comprehensive series of RF modem drive-around tests involving both the payload modem and ground node modems was executed. Aligning with the Lidar localization test methodology, the payload was mobilized on wheels, while the ground nodes were strategically positioned within the testing area. Each ground node was equipped with an individual RF modem.

A sequence of RF modem walk-around and drive-around tests were systematically conducted to assess the feasibility of utilizing RF modem data for localization. This series served as the initial phase of tests within the indoor experimental framework, setting the stage for subsequent outdoor evaluations preceding the actual flight test.

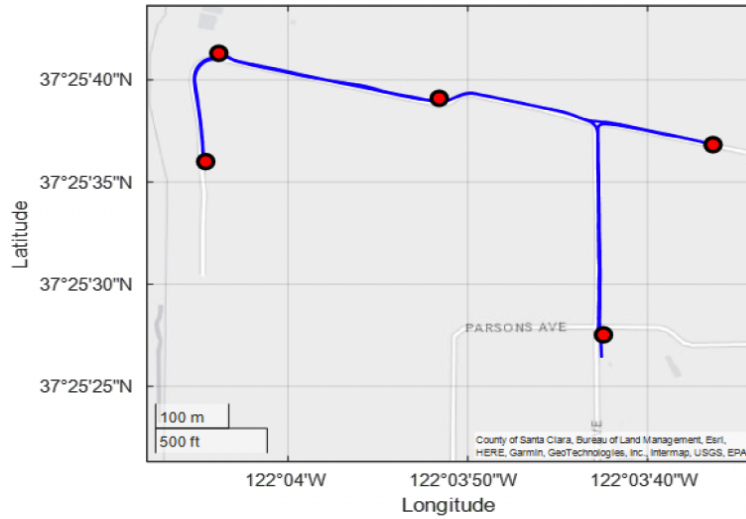


Fig. 30 Outline of the Path Taken During the Drive Test [23]



Fig. 31 Drive-Around Setup for the RF Mesh Modems

In the outdoor drive-around test, the primary objective was to replicate the flight test setup, requiring the placement of modems in identical locations to those of the actual sensor stations. The flight payload modem, housed in a car, underwent a meticulously orchestrated drive along the designated route, mirroring the anticipated flight path. Operating at speeds ranging from 5 to 10 mph, deliberate stops were made at each modem station to ensure proper data acquisition by the modems. Figure 31 depicts the vehicle, featuring the placement of the modem on its roof, with a colleague capturing an image of one of the ground station modems affixed to a plastic ladder. Figure 30 outlines the test route, featuring red dots strategically placed to mark the locations of RF modems. This placement strategy aims to enhance accuracy by establishing a denser network with multiple transmitters closer to the tracked object.

During this test, RSSI readings and GPS logdata were collected. GPS logdata facilitated the creation of synthetic RSSI readings per RF antenna location and calibration of RF antenna. Post-calibration values per modem were utilized in the sensor fusion observation model. Figure 32(a) illustrates noiseless synthetic measurements based on GPS

logdata, provided by different distributed wireless network transmitters. The upper half correlates measurements with range, revealing consistent RSSI magnitude levels beyond 100m. Figure 32(b) displays true measurements recorded by the receiver modem on the moving vehicle, contaminated by noise. A comparison between Figures 32(a) and 32(b) highlights the impact of noise on the RSSI signal. At longer distances, the dB difference between RF antennas diminishes, rendering them indistinguishable based on dB level alone due to noise. This noise level, particularly at extended distances, is anticipated to impede successful localization. Identifying the maximum noise level and other sensor characteristics critical for accurate position estimates, or combining them with other sensor measurements, is a key area of investigation.

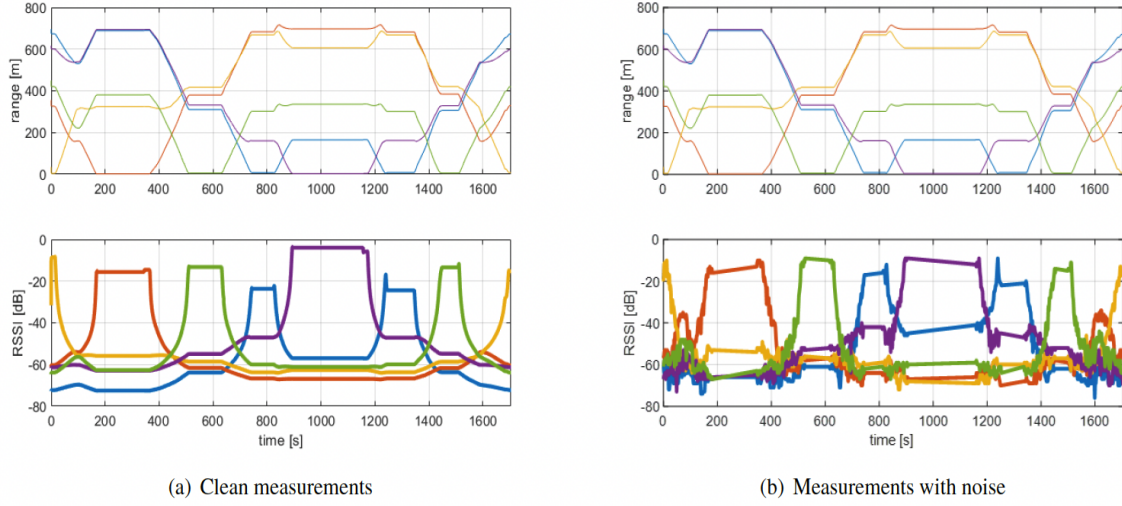


Fig. 32 RSSI Measurement Comparison Between the Ground Truth and the Test Output [23]

C. Flight Test Campaign with Distributed Ground Nodes

A sequence of flight tests transpired at NASA Ames Research Center from May to September 2023, specifically centered around the DART region of the facility. The designated test route and sensor locations are visually represented in Figure 33, with the sensor positions marked in yellow. The testing protocol involved multiple runs, each commencing from sensor station 3, following the prescribed route, and concluding with a landing at station 1. Subsequently, the flight started at station 1, and then retraced the route back to station 3. More information on the flight tests and the sensor locations can be found in [24].

In these flight tests, different datasets were systematically collected and utilized for the analysis of various distributed sensing algorithms. As an illustrative example, the images captured by the GoPro camera during a specific flight test are employed for the examination and validation of an algorithm designed for a vision-based object tracker known as Ground-Based Vision Tracker (GBVT).

The primary objective of GBVT is to track multiple objects in the airspace, such as Unmanned Aerial Vehicles (UAVs) and transmit the acquired data to the Ground-Based Object Tracker (GBOT) Extended Kalman Filter (EKF) to estimate the position and velocity of the tracked objects. Figure 34 visually represents the sequential steps of the GBVT pipeline. The initial window in the top left displays the original frame, featuring black masks to eliminate undesired regions and a rectangle delineating the region of interest (ROI). The subsequent window from the top left showcases the tracking performance within the ROI, denoted by a blue bounding box surrounding the UAV to indicate successful tracking. Moving to the third window from the top left, the background subtracted image is presented after eliminating all static objects' pixels, revealing only the UAV (depicted in white). The bottom left window incorporates a red circle around the latest detection (keypoint), accompanied by a bounding box. The last window exhibits several white dots, representing previous detections of the object, while the red dot signifies the presently tracked object, encompassed by a bounding box. Finally, the command prompt in the bottom right corner provides information on the current frame and the completion percentage, based on the current frame number and the remaining frames in the dataset. More details about the GBVT can be found in [22].

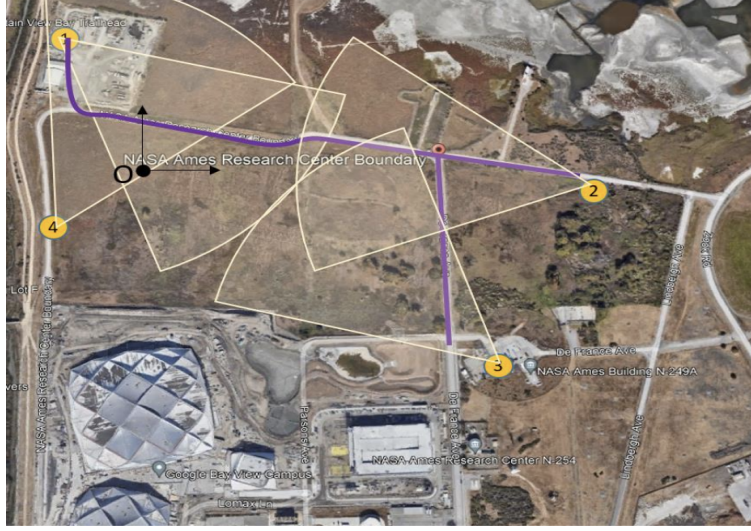


Fig. 33 Route Taken During the Flight Test

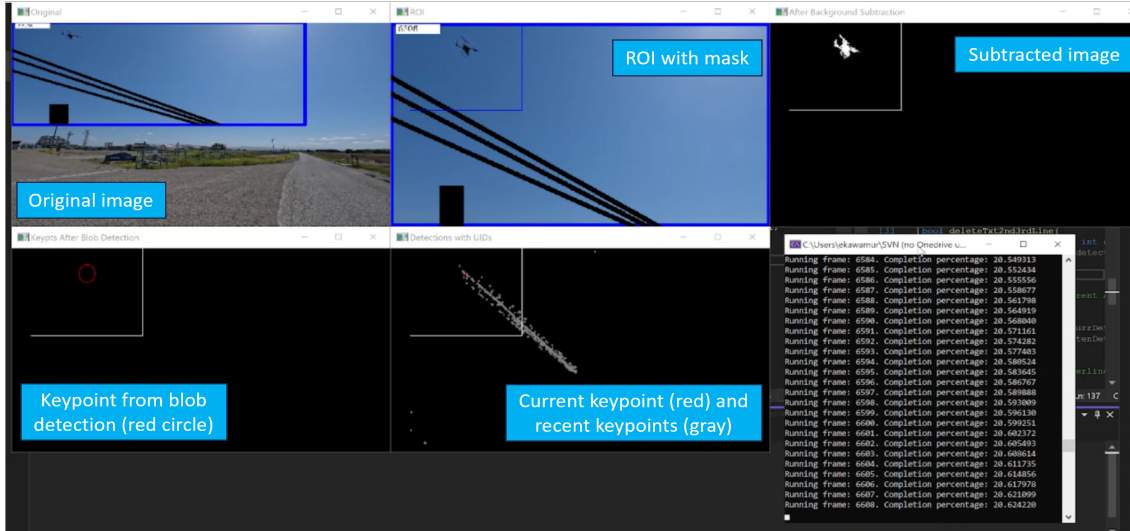


Fig. 34 Image Tracker Screenshot: Image Processing Pipeline for Ground Node 1 [22]

The EKF serves as the sensor fusion algorithm, integrating various measurements, such as RSSI from the RF modems and azimuth and elevation angles from processed camera images, to estimate the trajectory of the tracked object. The resulting estimated states encompass 3D position and velocity components. Notably, the utilization of camera-based information yields a significantly more accurate path estimate, attributed to the superior signal-to-noise ratio of camera measurements compared to RF modem signals. However, the precision of these estimates is contingent upon accurate location and viewing direction information, as well as calibration efforts across different ground nodes. For a comprehensive understanding of the sensor fusion algorithm's development for object tracking and detailed results from field tests, refer to [23].

VII. Conclusion

This paper introduces a framework for the distributed sensing concept designed to conduct comprehensive tests across various scenarios pertinent to Advanced Air Mobility (AAM). The outcomes of these tests are envisioned to establish a foundational baseline for future flight tests, incorporating a multitude of sensor nodes into the conceptual and scenario-specific frameworks. Notably, the challenge of achieving precise time synchronization across multiple nodes

remains a focal point requiring further attention.

Subsequent endeavors in this research trajectory will encompass the extension of the distributed sensing network to confront the unique challenges posed by outdoor environments. Additionally, dedicated efforts will be directed towards addressing the time synchronization difficulties. Future work includes the execution of multiple distributed sensing-based tests, specifically focusing on object detection, tracking, and precision approach & landing scenarios. These collective efforts aim to enhance the robustness and applicability of the distributed sensing framework in the context of AAM operations.

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