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Seeker 1.0: Prototype Robotic Free Flying Inspector Mission Overview

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ABSTRACT

Seeker 1.0 is a prototype free flying robot that will one day be capable of inspecting human-rated spacecraft. Building off previous free flyer experience, this technology will eventually improve safety of human spacecraft by offering a variety of inspection capabilities for both routine and emergency scenarios providing increased capability and safety over current inspection methods. Seeker 1.0 is capable of 6 degree of freedom flight via a cold gas propulsion system and can operate up to 1 hour via a semi-autonomous guidance, navigation, and control system. The prototype spacecraft is capable of capturing still images at a variety of resolutions up to 13 MP. The initial test flight utilizes a command and data relay box called Kenobi. Kenobi is a derivative of the Seeker design and will communicate between Cygnus and Seeker and store data for post-mission downlink. Seeker and Kenobi have launched inside a NanoRacks External CubeSat Deployer (NRCSD-E) attached to the NG-11 Cygnus ISS resupply vehicle and will operate after Cygnus departs ISS and moves to a safe altitude. Operations will last approximately 30 minutes and will consist of basic vehicle maneuvers while capturing high-resolution still images. With any remaining time and propellant, Seeker will demonstrate additional safety capabilities and maneuvers required for operations around a crewed spacecraft. The Seeker project utilized the Class IE process that allows for streamlined flight hardware development and increased mission risk tolerance.

INTRODUCTION

For over 20 years, the Engineering Directorate of the NASA Johnson Space Center (JSC) has sought to develop advanced robotic free flyer technologies for inspection of human spacecraft.[1] Recently, engineers took the next step in this effort, developing the Seeker 1.0 prototype CubeSat. Funded by ISS, this effort takes the first step in an evolutionary development approach towards a human-rated inspection tool. Once fully developed, Seeker has the potential to increase the safety of human spaceflight and establish rules of the road for safety enabling other free flyers to operate in close proximity to crewed spacecraft.

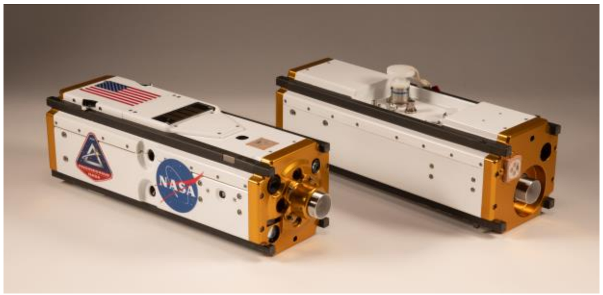

Figure 1: Seeker 1.0 (Left) and Kenobi (Right) Flight Vehicles

MOTIVATION

Human spaceflight needs advanced options for safe, low-cost, rapidly deployable external inspection of crewed spacecraft. Because of limitations with current technologies, inspection plays a limited role in spacecraft health monitoring. Were a more capable method available, such as Seeker, engineers could gain greater insight into overall spacecraft health and performance thus increasing the safety and capability of human spaceflight.

State of the Art

Currently, inspections are performed either by robotic arms or by astronauts during extravehicular activities (EVA) aka spacewalks. Both methods require extensive ground planning and on-orbit crew time, making them resource intensive and a poor fit for scenarios requiring a fast response.

Current inspection methods also pose unique safety concerns. EVAs present obvious risks to the astronauts performing them, while robotic arms, due to their large mass, could inflict critical damage to the spacecraft under inspection should recontact occur. There are also some types of inspections that are too dirty to be safely performed during EVAs. For example, searching for the source of a leaking hazardous fluid such as ammonia coolant or hydrazine propellant.

Neither astronauts nor robotic arms typically provide complete inspection coverage due to limited availability of handrails (for EVAs) or grapple fixtures (for robotic arms). This is true on large space vehicles such as the International Space Station (ISS), which has large, delicate external components such as solar arrays and radiators that are structurally incapable of supporting handrails and grapple fixtures. This is also true for vehicles with aerodynamic constraints required for atmospheric re-entry such as NASA's Orion, Boeing's Starliner, and SpaceX's Crewed Dragon.

Finally, many human spacecraft (Orion, Starliner, Crewed Dragon, etc.) have neither readily available EVA capability nor robotic arms to perform inspections. This makes inspections prior to some critical events such as entry, descent, and landing infeasible.

Advantages of Free Flying Inspectors

Although a limited number of basic spacecraft inspection needs are currently met with available technologies, their relatively large overhead means inspections are only performed when absolutely necessary. Were inspections easier and safer to perform, they could become routine. This means engineers on the ground would have greater insight into spacecraft health and performance, enabling better estimates of vehicle remaining life and making replacement predictions easier.

Free flyers have the potential to overcome many of the drawbacks of current inspection technologies. The possibility for partial or even fully autonomous inspection means the burden of routine inspection and documentation work are offloaded, freeing astronauts and ground controllers to perform more complex tasks not suitable for robots. This level of autonomy also means Seeker could be rapidly deployed in support of anomaly resolution.

Free flyers could also be safer than robotic arms due to their significantly lower mass. Even larger (6U) CubeSats weigh less than 10 kg[2]; whereas robotic arms typically weigh hundreds of kilograms or more.[3,4] This reduced mass means the consequences of recontact are less severe with free flyers assuming similar translation rates. This assumption is generally true given free flyers' inherent desire to conserve their limited propulsive resources.

Finally, since free flyers are untethered, they are capable of complete spacecraft surface inspection. Their compact size means they are readily incorporated into spacecraft as many already feature CubeSat deployment capabilities.[5]

Potential Use Cases

Seeker's compact size and operational flexibility lends it to many use cases for current and future human exploration. In the most sophisticated application, Seeker performs routine inspections of various sections of the host spacecraft on a weekly or monthly basis. Under this scenario, Seeker would be capable of operating autonomously in regions of the spacecraft that do not support real-time communication. After the inspection, Seeker would autonomously dock for data downlink, refueling, and power charging in preparation for the next predefined inspection. The high rate of recurrence leads to a desire to minimize human interaction. When added to the desire to operate in communication-denied regions, it mean inspections will be performed autonomously with no ground or crew involvement. Such scenarios are attractive to spacecraft with long mission durations such as ISS or a trans-mars tug and those which will be uncrewed for long durations such as Gateway.

Other likely scenarios are for rapid anomaly resolution or for inspection prior to or during critical spacecraft events such as atmospheric re-entry, docking, or berthing. Under these scenarios, Seeker would be a one-time use tool self-disposing once its mission becomes complete. Because of the single-use nature, more crew/ground involvement up to full tele-operation is less burdensome and is likely desirable due to the event's criticality. The potential low-cost of Seeker units created by the use of CubeSat commercial-off-the-shelf (COTS) hardware makes disposal financially feasible.

If the host spacecraft is small and has readily available attitude control such as Orion, it may be beneficial to deploy Seeker and have the host vehicle perform attitude maneuvers for the inspection. This would enable Seeker to image large sections of the host spacecraft at a low delta-V cost.

Eventually, Seeker will have a modular architecture that will incorporate a common vehicle bus and a sensor payload bay. This will allow custom sensor packages that meet the specific inspection needs of the specific host vehicle (ISS, Orion, Gateway, Mars transfer vehicle, etc.) while maintaining bus flight heritage. Envisioned sensor packages include stereoscopic cameras, infrared cameras, leak detectors, and LiDAR though others are possible. The sensor payload could also be used as a platform to house non-inspection related technology or science payloads.

A BRIEF HISTORY OF FREE FLYERS OPERATING AROUND CREWED SPACECRAFT

Autonomous Extravehicular Activity Robotic Camera (AERCam)

To date, the only external free flyer to operate in close proximity to a crewed spacecraft wass the Autonomous Extravehicular Activity Robotic Camera Sprint (AERCam Sprint) which was also developed by the Engineering Directorate of the NASA Johnson Space Center as a prototype inspector. AERCam Sprint flew in the Space Shuttle payload bay aboard STS-87 in 1997 (see below).[5] The mission lasted approximately 1 hour and 15 minutes and performed basic maneuvers while being piloted by astronaut Steven Lindsey from inside the Space Shuttle. AERCam Sprint was built in a 14 inch (36.6 cm) diameter spherical form factor weighing 35 lbm (15.9 kg). It featured 6 degree of freedom motion (DOF) via 12 cold gas nitrogen thrusters offset from the center of gravity. This meant a stuck on thruster would result primarily in an increase in rotational rates, not translational velocity. Because the free flyer did not have any corners, rotational velocity would cause minimal damage, were the vehicle to recontact the Space Shuttle or an astronaut on EVA. The system featured 2 cameras, one for navigation and the other for inspection.

Figure 2: AERCam Sprint retrieval after a successful demo in the Space Shuttle cargo bay during STS-87.[6]

A follow-on effort called Mini-AERCam (See Figure 3) was proposed and partially developed; however, it was canceled in the early 2000's due to programmatic reasons. The goal of Mini-AERCam was to develop a free flyer inspector for nominal use by miniaturizing the system's mass and volume, increasing propulsive capability, and increasing autonomy. The diameter was decreased to 7.5 inches (19.1 cm) and mass to 11 lbm (5 kg). The system maintained 6 DOF control via cold gas thrusters; however, the propellant was switched to Xenon, increasing the delta-V capability to 40 ft/s (12.2 m/s). The system included 1 high resolution still image camera and 2 color video sensors for navigation.

Figure 3: Mini-AERCam[6]

Internal Free Flyers

Since AERCam, several internal free flyers have been developed and flown including SPHERES (MIT)[8], Astrobee (Ames Research Center)[9], and Int-Ball (JAXA)[10]. These robots have applications ranging from technology development to hardware location to assisting astronauts. Several unique hardware difference exist between these internal platform and external platforms like AERCam and Seeker largely due to the different operating environment. For example, internal free flyers typically use fans for propulsive maneuvering. However, there is great technical overlap in the areas of autonomy and software architecture. The authors hope future Seekers will present opportunities for collaboration with these free flyers.

SEEKER 1.0 MISSION OVERVIEW

Goals and Objectives

Seeker 1.0 will demonstrate the basic capabilities required for safe external robotic free flyer inspection of crewed spacecraft. Additionally, in order to make post-mission disposal one day financially feasible by minimizing cost, it is desired to leverage the CubeSat and non-traditional aerospace components. However, CubeSats have a notoriously low reliability in part due to component reliability.[11] This low reliability becomes unacceptable when the failure could have serious consequences to human life or high-value assets. Thus, an additional programmatic goal is to determine how to reconcile these two conflicting realities. Finally, an internal organizational goal was to provide hands-on experience to early-career NASA employees and to develop a high performance team based on a culture of on-time execution through high velocity decision making. These desired technical, programmatic, and organizational goals are summarized in Table 1.

Table 1: Seeker 1.0 Goals

Goal 1:	Demonstrate safe operations around the host vehicle.
Goal 2:	Demonstrate core vehicle performance.
Goal 3:	Validate utilization of CubeSat and non-traditional aerospace commercial-off-the-shelf (COTS) hardware for critical spacecraft functions.
Goal 4:	Develop early career engineers through hands-on flight experience in a face-paced development environment.

These goals were decomposed into the following objectives that form the basis of the project requirements (note: first number links objective to goal, second number is the unique objective identifier):

Table 2: Seeker 1.0 Objectives

Objective 1.1:	Operate in proximity to the host vehicle without inadvertent recontact.
Objective 1.2:	Demonstrate core vehicle safety design features.
Objective 1.3:	Establish safe "rules of the road" for free flyers operating around human spacecraft.
Objective 2.1:	Demonstrate Seeker visual inspection capabilities.
Objective 2.2:	Demonstrate core Seeker vehicle maneuverability.
Objective 3.1:	Utilize non-traditional aerospace COTS components where possible.
Objective 4.1:	Include early career employees in key leadership and technical roles.
Objective 4.2:	Streamline practices and processes for efficiency.

It is important to note that due to resource limitations, Seeker 1.0 was a cost and schedule-oriented project. Early project discussions with ISS leadership made it clear that a great deal of technical risk associated with mission success (not safety) was acceptable; however, cost and schedule were fixed. Because of this, technical goals and objectives became best-efforts with any shortfalls moving to future development. This lead to objective statements that are more open-ended than usual.

One objective of note is objective 1.3: *Establish safe "rules of the road" for free flyers operating around human spacecraft*. This objective is a corollary to the goal of safe operations. Currently, NASA does not have an effective way of determining whether a free flyer operating near crewed spacecraft will pose a threat. Because of this, previous free flyer proposals were declined. Seeker hopes to establish basic design and operating guidelines for safe operation around human spacecraft. These guidelines will not be hard and fast rules, rather a point of reference for assessing safety. The intent is to open opportunities for future free flyers to operate near crewed spacecraft.

Mission Architecture

A key strategy in the Seeker 1.0 approach was to architect the mission to be inherently safe to human life and critical space assets such as ISS. This enable an aggressive technical approach while living within the fixed schedule and cost resources. This strategy was implemented by operating around a Northrop Grumman Innovation Systems (NGIS) Cygnus vehicle after it has unberthed from ISS and moved to a safe altitude such that Seeker would pose no more of a threat to ISS than any Cygnus-deployed CubeSat.

Cygnus was selected over other ISS cargo vehicles because of its existing ability to accommodate the NanoRacks External CubeSat Deployer (NRCSD-E). The NRCSD-E, seen in Figure 4, consists of 6 1U by 6U tubes (36U total) and is mounted to the side of the Cygnus service module. Two tubes of CubeSats are held in place behind each of the three doors that are commanded by Cygnus.

Another advantage of using Cygnus was its existing secondary payload interfaces that were developed for NASA's Spacecraft Fire Safety (Saffire) experiments. This locked interface definitions such as software communication protocols, connector pinouts, allowable electromagnetic interference, and power conditioning requirements early in the project life cycle. Designing Seeker 1.0 to fit existing interfaces enabled the rapid development schedule and also controlled cost.

The decision to use Cygnus had major mission architecture implications. First, Cygnus does not provide any means of wireless communication with secondary payloads. Second, Cygnus secondary payloads are limited to 8 kb/s real-time data rate to the ground during operations. These two limitations lead to the necessity of a command and data relay and data storage box. This box, named Kenobi, is stowed in the tube adjacent to Seeker and is not deployed. Kenobi transmits commands from Cygnus to Seeker via 5 GHz Wi-Fi and will store engineering data and images gathered by Seeker during the mission. Following flight operations, Kenobi will be periodically powered on to transfer flight data and images to Cygnus for downlink during ground communication passes, which have higher data transfer rates. This will allow for up to 35 Gb of data to be transferred over a period of seven days. Kenobi is also responsible for signaling Seeker to power on inside the NRCSD-E prior to deployment.

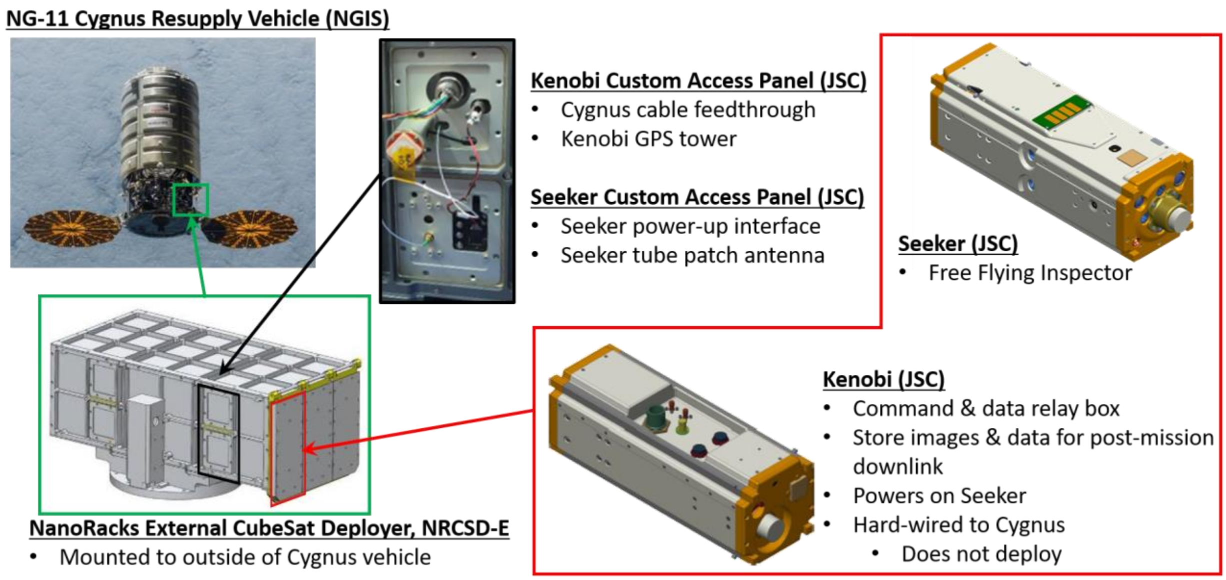

Figure 4: Seeker 1.0 Major Mission Elements

Kenobi was interfaced with Cygnus through removable panels on one face of the NRCSD-E that were replaced by custom designed panels to support cables running from Kenobi's tube to Seeker's tube and a custom designed, low-profile patch antenna. Finally, Kenobi is outfitted with a camera that will take images of Seeker during operations for post-mission best estimated trajectory analysis.

The low data rate to the ground during mission operations made teleoperations impossible, increasing the level of autonomy and creating the need for a full guidance, navigation, and control (GN&C) subsystem. This resulted in a significant increase in cost and system complexity.

Concept of Operations

The Seeker 1.0 mission was selected to fly aboard NG-11 due to schedule alignment with launch dates. After its three-month stay at ISS, the NG-11 Cygnus will unberth and move to an altitude 56 km above ISS. This altitude ensures that if Seeker expends all propellant immediately upon deployment, ground crews will have enough time to track it and maneuver ISS to a safe orbit if necessary. Cygnus will also orient to put the Seeker deployment velocity along the orbital velocity vector and go into a local vertical, local horizontal (LVLH) hold where it will stay throughout the mission.

Once at the appropriate orbit and attitude, Cygnus powers on Kenobi and establishes communication. Next, ground commands will be sent to power on Seeker from Kenobi. Seeker's batteries and thrusters will undergo an automated 15 minute warmup sequence after which Seeker's main flight computer boots and communication with Kenobi established. Just prior to deployment, Seeker's navigation algorithms start and inertial measurement unit (IMU) bias estimation is performed for 90 seconds. Seeker is now ready to deploy.

As soon as possible after the IMU bias estimation is complete, the NRCSD-E door opens, deploying Seeker at a velocity of approximately 0.5 m/s. Seeker will coast for approximately 1 second after which it will fire thrusters to offset any tip-off rates imparted during deployment. At 9 m from Cygnus, Seeker will begin active target tracking by orienting its cameras towards Cygnus. Seeker will then coast at the deployment velocity, only performing thruster firings to continue tracking Cygnus and to maintain a velocity vector along Cygnus' orbital velocity vector. This is necessary due to the orbital effects caused by the increased velocity during deployment. Seeker will execute a braking maneuver to come to rest at 30 meters from Cygnus. Once stopped, Seeker will take six high resolution photos of Cygnus and hold for ground commands to proceed. This hold will allow the Seeker flight team to assess Seeker's health and verify adequate tank pressure, battery voltage, and available lighting for the next portion of the mission.

The next set of maneuvers translate Seeker 5 meters "down" and "over" in a plane parallel to Cygnus. After a hold for ground checks, Seeker will then move towards and away from Cygnus. After another hold,

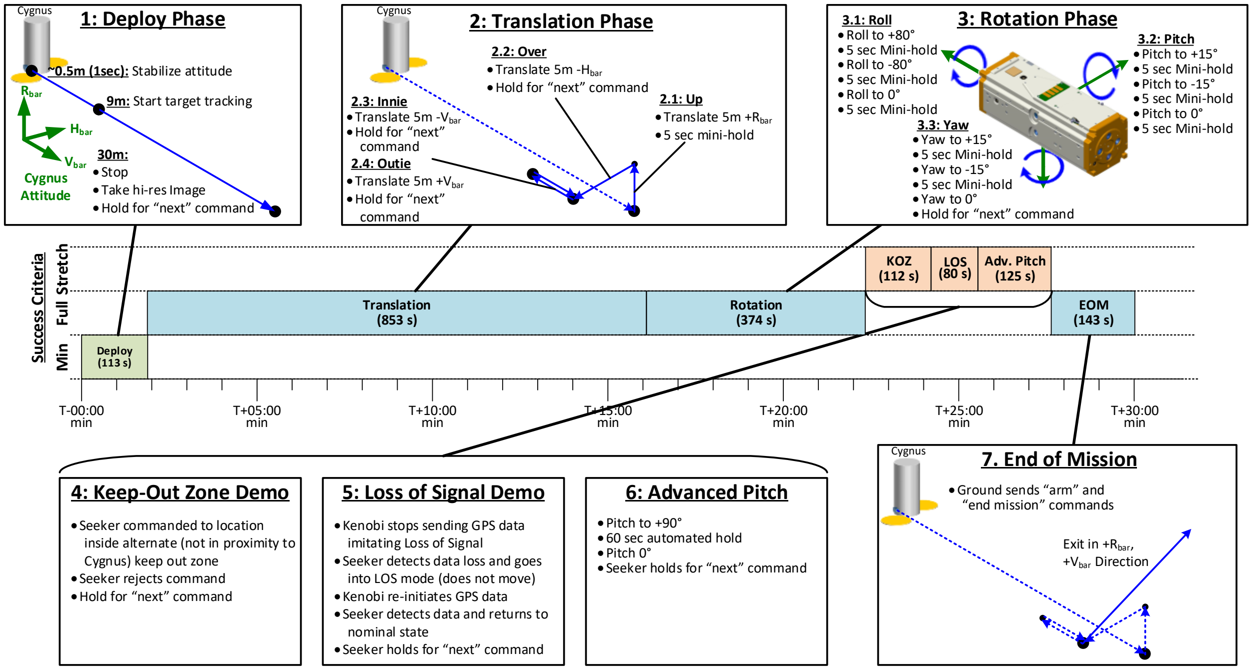

Figure 5: Seeker 1.0 Operational Concept

Seeker will perform small roll, pitch, and yaw maneuvers.

The final portion of the mission will demonstrate advanced safety features. The first feature is acknowledgement of a keep-out zone. Seeker will be commanded to a waypoint inside an artificially created keep-out zone. If successful, Seeker will reject the command and hold for the next command. The waypoint is located a safe distance from Cygnus in order to prevent recontact if Seeker fails to obey its keep-out zone. The next phase will be to demonstrate automated response to loss of communication. During this phase, Kenobi will stop sending GPS data packets, which Seeker will interpret as a loss of communication, causing Seeker to go into a unique loss of communication mission mode and hold its position until communication is reacquired. If this data is not re-established, Seeker will hold indefinitely; however, Kenobi is programmed to re-initiate data transfer after 10 seconds, causing Seeker to transition back to a nominal state and wait for a next command. It's important to note that during this phase, communication is not actually lost. Seeker thinks it is lost because it is keying off GPS data packets from Kenobi to determine its communication state. Finally, Seeker will perform an advanced pitch maneuver causing communication to transfer from one antenna to another and taking Cygnus out of view of Seeker's navigation camera. Current analysis shows Seeker will likely not have enough propellant to initiate the advanced pitch maneuver; however, the team wanted to have adequate tasks planned in case Seeker performs better than expected.

Table 3: Seeker 1.0 Mission Success Criteria

	Minimum	Full	Stretch
Purpose:	*Demonstrate minimum vehicle maneuverability and inspection capability.*	*Demonstrate core vehicle maneuverability and inspection capability.*	*Demonstrate additional vehicle safety features.*
Objectives:	1. Deploy 2. Self-arrest 3. Take ≥ 1 high resolution image 4. Transmit ≥ 1 high resolution image	1. Translate in 3-DOF 2. Rotate in 3 DOF 3. Obey a speed limit 4. Image resolution sufficient for inspection 5. Self-dispose.	1. Obey a keep-out zone. 2. Response to loss of comm. 3. Transition comm. from one antenna to another. 4. Lose sight of host vehicle and reacquire it.

The overall mission should take approximately 30 minutes. Once all phases have been successful, or if at any hold period the Seeker team determines there is not adequate propellant, battery, or lighting to continue, an "End of Mission" command will be sent causing Seeker to self-dispose on a safe trajectory.

At any time, the Seeker or NGIS flight teams can call an abort and inhibit Seeker's propulsion system. In the event of a failure, this is the safest course of action since a failure will likely cause Seeker to lose its capability to navigate. Thus, Seeker can no longer determine which direction is safe to dispose. If an abort is issued, Cygnus will immediately depart on a pre-defined safe trajectory.

Mission success criteria (minimum, full, and stretch) were established and are seen in Table 3. Note that in conjunction with inspection stakeholders, the minimum inspection resolution required is defined as capturing a 64 mm (1/4 inch) feature at a resolution of 8 by 8 pixels from 10 meters away. The inspection distance of 10 meters was selected from discussions with the Mini-AERCam team.

VEHICLE OVERVIEW

Seeker 1.0 hardware includes the Seeker free flyer, Kenobi command and data relay box, and two custom interface panels.

Seeker

The overall Seeker free flyer performance specifications are in Table 4.

Table 4: Seeker 1.0 Specifications

Size	3U
Mass	4.2 kg
Battery Capacity	35 Whr (provides approx.. 1 hour of operations)
Attitude and position control	6 DOF control via 12 cold gas thrusters
Propellant	Nitrogen gas (provides 5.8 m/s linear delta-V)
GNC Sensor Suite	IMU GPS Sun Sensors (x4) Laser rangefinder Vision based navigation using neural network
Communication	5 GHz Wi-Fi
Imaging Capability	Up to 13 megapixel

Seeker includes all subsystems traditionally found in an uncrewed spacecraft. Wherever possible, non-traditional aerospace COTS and CubeSats components were used to control cost and schedule. Additionally, whenever possible, components were used which had spaceflight heritage either through the team's experience or by other CubeSat developers. When heritage data was not available, components were qualified in-house for the mission environments such as thermal, vibration, shock, radiation, and vacuum.

Seeker utilizes Core Flight System (cFS)[12] as the software backbone. This greatly accelerated the software development and verification process since cFS provides the core vehicle operating functions and has a diverse library of modules for interfacing with sensors and GN&C algorithms.

Seeker includes a full suite of GN&C algorithms that provide 6 DOF vehicle control.[13] Seeker is commanded via waypoint guidance and leverages a diverse set of navigation sensors (see Table 1) which are fed into a Kalman filter to create the navigation state. Seeker's navigation algorithms also leverage a GPS antenna located on the Kenobi Interface Panel to initialize the state and help in determining its relative position during operations. One unique aspect of Seeker's GN&C subsystem is its vision-based system navigation developed through a partnership with the University of Texas at Austin. This system uses images gathered from the navigation camera to identify and localize Cygnus by utilizing a neural network that has been "trained" to recognize Cygnus. Once Cygnus is identified, the network draws a box around it and uses traditional computer vision algorithms to bound Cygnus and identify its geometric center. This effectively provides Seeker's bearing to Cygnus.

Seeker's avionics consist of a main flight computer, flight computer interface board, camera image processor, and the propulsion controller. The general avionics philosophy was to use as many COTS components as possible designing custom components only as required to integrate COTS components. Because of this, only the flight computer interface board and propulsion controller required custom builds. Additionally, the camera image processor was quasi-custom design that connects a COTS processor and USB to Ethernet hub.

Seeker's power is provided by COTS CubeSat power source consisting of four 18650 Lithium-Ion batteries connected in series to provide 35 Wh of power on a 15 VDC bus. This is enough power to operate Seeker for approximately one hour. Seeker's power is regulated down to 12, 5, and 3.3 volts dc via two COTS CubeSat power distribution units (PDU) creating 18 commandable power channels. Future designs will likely incorporate solar arrays for increased mission duration.

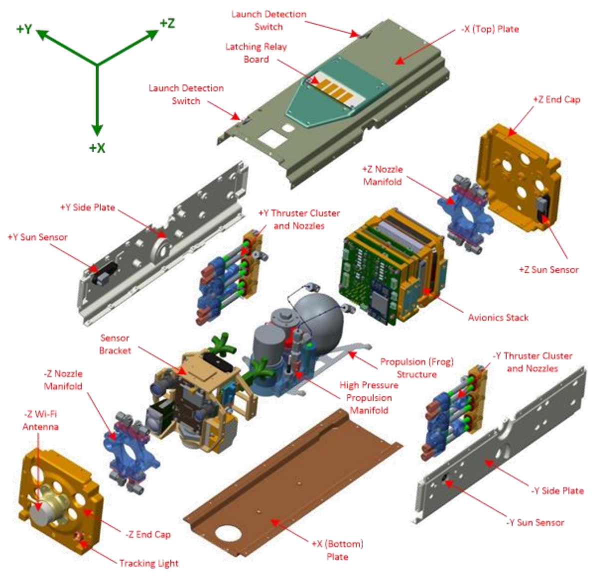

Figure 6: Seeker Exploded View

Seeker communicates via 5 GHz Wi-Fi which is provided by the camera interface processor. The wireless communication system utilizes two antennas (on the vehicle -Z and +X faces) each providing hemispherical coverage. Based on this design, conservative link budgets estimate Seeker and Kenobi will be able to communicate at a distance of 40 meters and likely much further.

The propulsion subsystem consists of a 12 cold gas Nitrogen thrusters canted at 30 degrees and offset from Seeker's center of gravity. Similar to AERCam, this ensures a failed-on thruster will not result in pure translational velocity. The core of the propulsion system is the high pressure manifold which resides in the middle of Seeker and consists of machined block of aluminum onto which the tank, isolation valve, pressure regulator, and pressure relief devices mount. These components are fluidically connected via integrally machined channels. Low pressure Nitrogen is fed to medium pressure manifolds on the + and – Y faces of Seeker. The medium pressure manifolds each house six thruster valves and two thruster nozzles. The remaining eight thruster nozzles are located on the + and –Z faces of Seeker and consist of 3D printed plastic.

Physically, Seeker is laid out in threee major modules, (Sensor Bracket, High Pressure Propulsion Module, and Avionics Stack) each approximately 1U in size. (see Figure 6). These modules are held together by the six sides of the outer mold line that also serve as the primary structure and passive provide thermal radiation. Although bent sheet metal was initially considered to control cost, all six sides were eventually machined out of aluminum to provide greater design freedom.

Kenobi

To reduce complexity and cost, Kenobi is a simplified version of Seeker. Kenobi features a sensor bracket that was stripped down to include one camera, one sun sensor, and a GPS. Since Kenobi doesn't deploy, there is no propulsion system. Finally, the avionic stack is very close to Seeker's design with the notable replacement of the battery with a DC-DC voltage regulator to step down Cygnus power to Kenobi's operating voltage. The –X face of Kenobi features electrical connectors to interface with Cygnus and the Seeker-side custom interface plate.

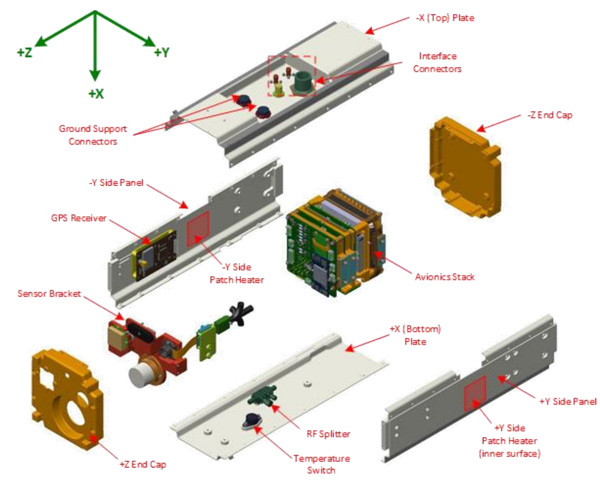

Figure 7: Kenobi Exploded View

Seeker to Kenobi Integration While Inside the NRCSD-E

As shown in the functional diagram in Figure 9, the location of Seeker and Kenobi in adjacent tubes enable the key functions of Seeker power on and pre-deployment ground communication.

Whereas most CubeSats utilize depress switches and a timer to power on after pre-set time after deployment, Seeker must power on while inside the deployment tube. Seeker takes approximately two minutes to power on, thus were the vehicle to begin power on after deployment, Seeker would be 60 m from Cygnus, over twice the desired distance. With the added 15 minutes of warmup time, this distance increases to 510 meters, likely out of range of communications and certainly too far for Seeker's limited propulsive capability to overcome.

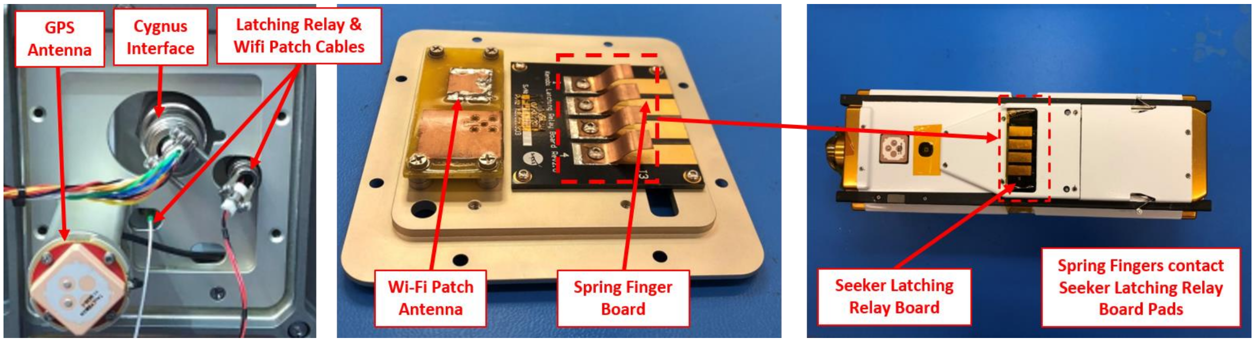

Figure 8: Kenobi side (left) and Seeker side (middle) Custom NRCSD-E Interface Panel

The task of powering Seeker on while still inside the NRCSD-E is accomplished through a latching relay on Seeker that is mounted to the underside of a simple printed circuit board with hard gold pads. Another board with spring fingers (see Figure 8) is mounted onto the NRCSD-E. The spring fingers press against the Seeker latching relay pads, making an electrical connection. These spring fingers are hardwired through a hole in the Kenobi tube's custom interface panel to a connector on Kenobi which is wired to two channels (one on, one off) of Kenobi's PDU. This allows the Seeker team to remotely power on and off Seeker from the ground. Since this connection cannot support shear loading, it does not significantly impact the required deployment force.

The next critical function is to establish ground communication with Seeker prior to deployment. Although wireless communication was eventually shown to travel from Kenobi's tube to Seeker's, early in the project lifecycle this was a large uncertainty that was mitigated through the implementation of a small Wi-Fi patch antenna on the inside of the Seeker custom access plate. This antenna is hardwired into Kenobi through a hole in the Kenobi access plate and ensures Kenobi, and thus ground teams, will be able to communicate with Seeker prior to deployment. This allows for initializing Seeker's navigation state with Kenobi's GPS solution and also allows for Seeker health verification prior to commitment to deployment.

SAFETY AND MISSION ASSURANCE APPROACH

Given Seeker's aggressive schedule, traditional NASA processes had to be heavily tailored. A zero-baseline approach was taken where all standard NASA and JSC processes associated with mission assurance were assumed inapplicable and tailored in only when their value had been justified. All requirements and processes associated with the health and safety of ground personnel, astronauts, and the safety of ISS were followed. These were treated as inflexible and non-negotiable. This approach of zero-baselining mission assurance processes without compromising safety is known at NASA as the Class IE Process. Although this type of hardware is to be flown in space (Class I), it is such that failure to operate does not pose a risk to astronauts or critical space assets and thus the hardware may be experimental (E) in nature, having a lower reliability. In the end, several traditional NASA processes such as controlled storage, Task Performance Sheets (TPS), configuration management, etc. were implemented in a streamlined fashion utilizing in-house developed tools in Microsoft SharePoint.

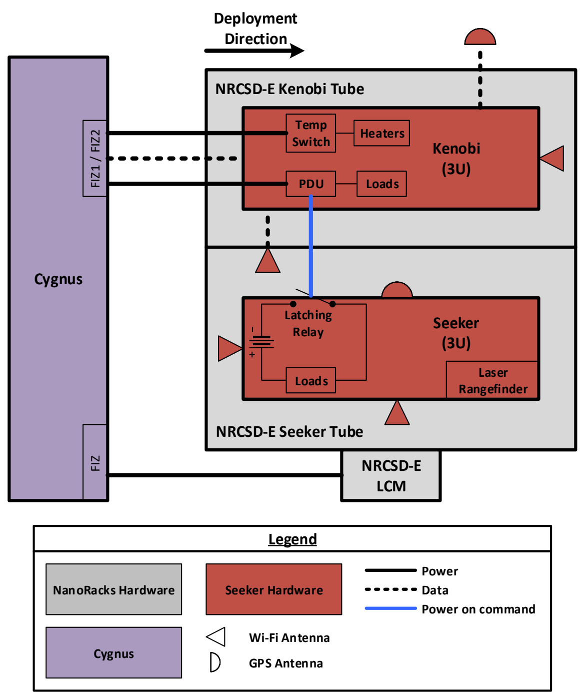

Figure 9: Seeker 1.0 Functional Diagram Showing Flight Installation into the NRCSD-E

It's important to note that NASA's traditional processes are valuable lessons learned through decades of hard-earned experience. Seeker was not an exercise in forgetting these lessons, rather a focus on finding and leveraging the true purpose and value of each lesson all while balancing technical risk with schedule and cost.

SYSTEM DEVELOPMENT APPROACH

As with mission assurance, aggressive approaches were required in the development approach to enable on-time delivery. A bunker approach was taken where team members were co-located in a small lab through the duration of development and acceptance testing. This approach lead to a flat organization structure, streamlined communication, rapid decision velocity, and tight team cohesion.

A systems engineering approach which blended agile and traditional approaches was taken. Emphasis was given to early and frequent hardware/software integration (HSI) milestones. This lead to cyclic development approaches where system capability was incrementally developed and infused into the system. Several tradition key decision points were merged and the preliminary design review (PDR) split with some content presented with systems requirement review (SRR) and the rest with the critical design review (CDR). The HSI milestones also had the unanticipated effect of building a strong team culture which emphasized execution and meeting deadlines.

CURRENT STATUS

Seeker was delivered on time and on budget and launched aboard NG-11 on April 17, 2019 with operations scheduled for late July.

Plans for Seeker 2.0 are underway; however, to date funding has not been secured.

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