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RAPID DEVELOPMENT OF THE SEEKER FREE-FLYING INSPECTOR GUIDANCE, NAVIGATION, AND CONTROL SYSTEM

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Seeker is an automated extravehicular free-flying inspector CubeSat designed and built in-house at the Johnson Space Center (JSC). As a Class 1E project funded by the International Space Station (ISS) Program, Seeker had a streamlined process to flight certification, but the vehicle had to be designed, developed, tested, and delivered within approximately one year after authority to proceed (ATP) and within a $1.8 million budget. These constraints necessitated an expedited Guidance, Navigation, and Control (GNC) development schedule, development began with a navigation sensor trade study using Linear Covariance (LinCov) analysis and a rapid sensor downselection process, resulting in the use of commercial off-the-shelf (COTS) sensors which could be procured quickly and subjected to in-house environmental testing to qualify them for flight. A neural network was used to enable a COTS camera to provide bearing measurements for visual navigation. The GNC flight software (FSW) algorithms utilized lean development practices and leveraged the Core Flight Software (CFS) architecture to rapidly develop the GNC system, tune the system parameters, and verify performance in simulation. This pace was anchored by several Hardware-Software Integration (HSI) milestones, which forced the Seeker GNC team to develop the interfaces both between hardware and software and between the GNC domains early in the project and to enable a timely delivery.

INTRODUCTION

During the 2017-2018 calendar year (CY), the JSC Engineering Directorate developed a 3U CubeSat for a proximity operations technology demonstration mission to take place on-orbit in 2019. The spacecraft, called Seeker, will be another step towards a capability long desired at JSC, an autonomous free-flying vehicle available for in-space inspection and situational awareness. Seeker is not an acronym; its namesake is the free-flying droid used by the Jedi for lightsaber training. This name is particularly suitable given one of the secondary purposes of the Seeker project, to give early career engineers at JSC the valuable experience of end-to-end responsibility on a flight project. Seeker presented many challenges, notably the rapid development pace required to deliver the vehicle within approximately one year. This timetable demanded that the Seeker GNC team use lean development practices and quickly assess necessary compromises to assemble a system capable of fulfilling the mission objectives given the project time and budget constraints.

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THE SEEKER PROJECT

The primary objective of the Seeker mission is to demonstrate a path toward an inspection capability for future crewed space missions. Such a craft could perform a multitude of tasks such as periodic inspections of a host spacecraft's solar panels or engine bell on long-duration missions, assessing damage after an orbital debris strike, leak detection, or providing an external free-flying view of critical events. These activities would otherwise require advanced planning on uncrewed missions or require a time-consuming and expensive extravehicular activity (EVA) on crewed missions.

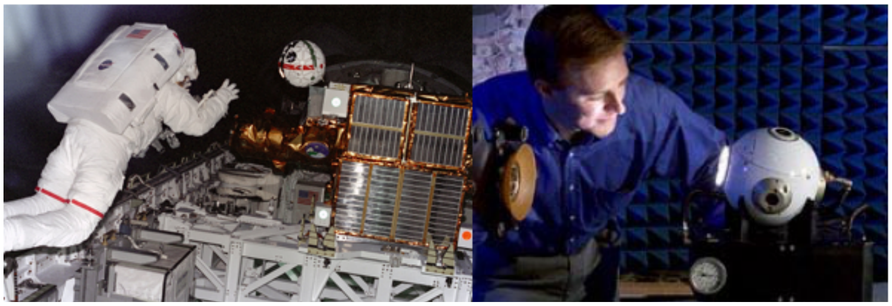

Figure 1. AERCam Sprint on STS-87 (Left) and Mini AERCam in a lab at JSC (Right)

The concept of an inspection craft for spaceflight is not a novel idea. The AERCam Sprint experiment flew aboard STS-87 in 1997 and was teleoperated by Shuttle astronauts. A follow-on mission, Mini AERCam, was in development throughout the 2000s, demonstrating capabilities on an air-bearing table at JSC but never flying.[1] These vehicles are shown in Figure 1. The emergence of the CubeSat market and a demand for small, reliable satellite components has mitigated the cost barrier, making the development of an inspection satellite a viable and attractive prospect.

Seeker was funded by the ISS Program as a Class 1E project, a relatively new NASA hardware classification that streamlines processes and clears a path to flight certification for small technology demonstration projects. Seeker received ATP from the ISS Program on July 26, 2017, with a $1.8 million budget and an allocation of 10 full-time equivalent (FTE) for labor, giving the team just over 14 months to design, develop, integrate, and test the spacecraft before the delivery date of October 1, 2018. Seeker and its communication link, called Kenobi, shown in Figure 2, will launch aboard a NanoRacks CubeSat Deployer (NRCSD) mounted outside a Cygnus Enhanced spacecraft on the NG-11 resupply mission to the ISS in 2019. After Cygnus completes its re-supply mission, unberths, and leaves the vicinity of ISS, Seeker will deploy on a roughly 45-minute mission with flight data and video logged onboard Kenobi to be telemetered down over the following weeks before Cygnus re-enters the Earth's atmosphere.

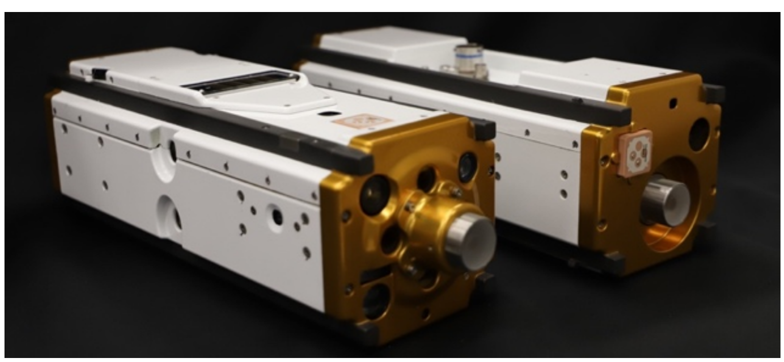

Figure 2. Seeker (Left) and Kenobi (Right)

SELECTING THE SEEKER SENSOR SUITE

One of the immediate challenges facing the Seeker GNC team after receiving ATP was determining the components of a sensor package capable of completing the mission. Mission objectives dictated that Seeker must demonstrate both translational and rotational control. Vehicle constraints required the use of sensors with very low size, weight, and power (SWaP). The original Seeker concept called for a completely teleoperated spacecraft. When it became clear that on-orbit downlink/uplink limitations made teleoperation infeasible, Inertial Measurement Unit (IMU)-only dead reckoning was then considered as the smallest change from the original baseline. Preliminary analysis indicated that IMUs that met the SWaP requirements would not meet the position, velocity, and the pointing requirements for the mission. Consequently, the GNC team needed to quickly determine what additional sensors could be added to the navigation system to achieve sufficient performance before proceeding with sensor procurement and algorithm development. A 6 degree-of-freedom (DOF) simulation for analysis and trade studies was months of development away from maturity, and prospective sensor lead times were already creeping into the project schedule's critical path. Therefore, Linear Covariance (LinCov) analysis was used to quickly perform the sensor trade.

Linear Covariance (LinCov) Analysis

LinCov analysis has a long history at NASA, dating back to the Apollo Program. As the name implies LinCov utilizes linear system theory to provide insight into the system performance similar to Monte Carlo analysis, but with a single run. Compared to Monte Carlo, which generates performance statistics from hundreds to thousands of simulation runs, LinCov only requires a single simulation run to obtain much the same types of performance statistics. Indeed, it is a useful tool to iterate on system design, especially in early phases of a project when design decisions are timely. By the time of Seeker, a LinCov framework already existed for LEO rendezvous mission analysis. Given its heritage, this framework was adapted and used to conduct Seeker mission and GNC system performance analysis for different sensor suites.

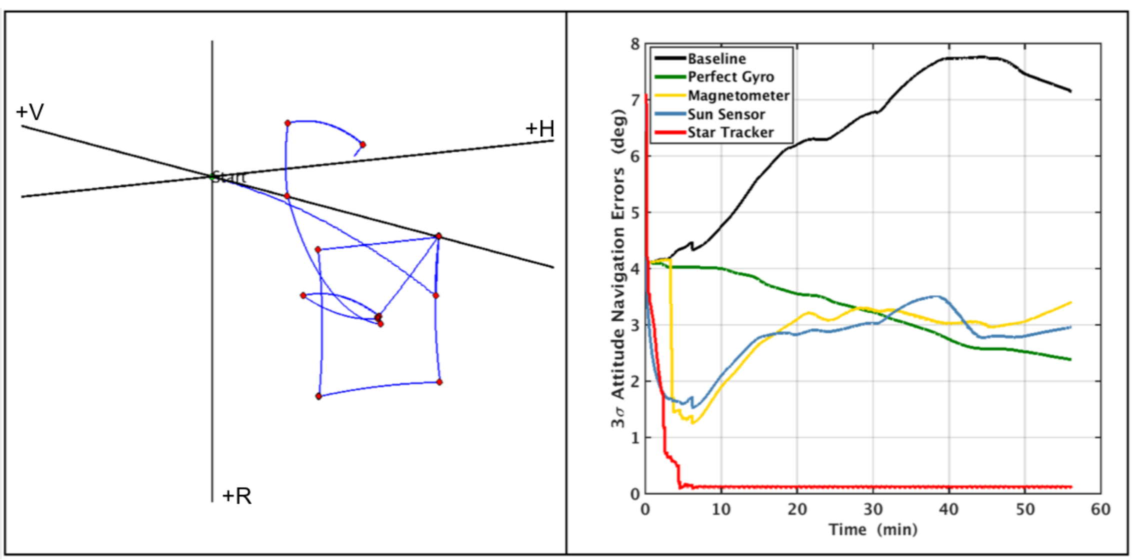

Figure 3. Early nominal trajectory profile (Left) and attitude navigation errors (Right)

The LinCov framework was setup to fly the Seeker mission profile, which at the time consisted of three phases: deploy, demonstrate 6 DOF control, and demonstrate vehicle inspection. The left visualization in Figure 3 shows the Seeker mission trajectory profile as modeled in LinCov. Each mission phase imposed requirements on the GNC system. After several design iterations, a baseline sensor configuration was established which met mission requirements with the exception of attitude accuracy. The initial baseline included an IMU, range finder, differenced GPS, and a generic bearing sensor. To meet the attitude accuracy requirement, an attitude sensor was added to the baseline configuration. LinCov was used to analyze three different attitude sensors, a magnetometer, a sun sensor, and a star tracker. The right subplot of Figure 3 shows the navigation attitude accuracy of the initial baseline configuration (black) and the performance with an addition of an attitude sensor (yellow, blue, red). The LinCov performance results were just one part of a larger trade study that also traded cost and lead-time, which ultimately favored the selection of a sun sensor.

Sensor Downselection

As LinCov had shown that the basic mission requirements could be met with a sensor suite comprised of IMU, a range sensor, a sun sensor, differenced GPS, and a bearing sensor, the driving factors for sensor selection became (in order) cost, performance, lead time, and heritage. In general, sensors that were designed for the space environment and had significant flight heritage were preferred. Should those not be available, units with little to no flight heritage that were designed for use in the space environment were considered alongside tactical-grade items that had some flight heritage.

For the IMU, traditional frontrunners of this type of sensor (e.g. SIGI, SDI500, LN200S) were too large, required too much power, were too expensive, and had too long of a lead time. A space-rated unit that fit the above constraints was not found within the allotted timeframe. Units designed for the space environment, but with little to no flight heritage were considered alongside tactical-grade units. Given the compressed schedule, low cost of the units, and uncertainty of their robustness to the space environment, two types of IMUs were purchased for parallel evaluation—the Sensonor STIM 300-400-5 and the Analog Devices ADIS 16490. As sensor procurement proceeded, the project became aware that Goddard Space Flight Center (GSFC) had been assessing the STIM units for use as part of the Raven package onboard ISS on STP-H5, and the units had shown promising results in environmental and performance testing for a Micro-Electro-Mechanical System (MEMS) IMU.[*] Leveraging GSFC's experience, the Sensonor STIM IMU was chosen for Seeker.

For the range measurement, several approaches were considered. Given the target was effectively uncooperative and considering the aforementioned SWaP and mission requirements, tactical, industrial, and drone laser altimeters were considered. Like the IMU, several laser rangefinder (LRF) units were selected to be evaluated in parallel. These were the Jenoptik DLEM-SR, the Jenoptik LDS30, and the LightWare LW20 (all class 1/1M). The DLEM-SR was selected as it was flown aboard the Optical Communications and Sensor Demonstration (OCSD)-A spacecraft and was slated to fly on the OCSD-B and OCSD-C spacecraft. The remaining sensors were selected based on a trade study of their SWaP.

Unlike the other sensor types, a number of options with heritage and very low SWaP exist for sun sensors. This being the case, the driving factors for selection then became cost and lead time, leading to the procurement of SolarMEMS nanoSSOC-D60 units.

For the differenced GPS measurements, two L1 channel GPS units were required. A performance constraint specific to these units was a minimal time-to-first-fix (TTFF), as Seeker would likely be unable to acquire while in the NRSCD and the mission time was approximately 45 minutes. While a variety of flight heritage GPS units were available as space-rated COTS products,

[*] https://sspd.gsfc.nasa.gov/Raven.html

the SWaP requirement and the TTFF requirement drove the selection of the SkyFox Labs piNAV-NG receiver.

For bearing measurements, camera-based and LiDAR-based methods were considered. At the time, no solid-state LiDAR met the SWaP, cost, and lead time requirements, which drove the selection of a camera-based system. A COTS solution was not found during the limited sensor selection period. Given the lack of existing solutions, recent experience with traditional computer vision approaches, and the promise of convolutional neural networks (CNNs), another parallel assessment effort was chosen. The three approaches selected for parallel development were a traditional approach based on scale-invariant feature transform (SIFT) algorithms, a pure convolutional neural network approach, and a convolutional neural network frontend with a contouring backend.

Sensor Testing and Verification

As the project had driven the selection of COTS sensors which weren't built for the space environment, it was necessary to create a test series to evaluate those candidate sensors to ensure they would perform as required during the mission. The space-rated COTS sensors were assumed to meet their environmental specifications and would have their performance verified in the lab environment upon delivery, but would not be individually evaluated for their rated environments. All sensors would again be subject to environmental testing when the integrated vehicle went through such testing.

The test series began with a set to ensure that the units performed as advertised. These were simple benchtop lab tests that involved operating the sensors within their rated environments and confirming that their performance matched their advertised specifications. The performance of several units failed to meet their advertised specification. The manufacturers were notified and had varying responses: from issuing new drivers, to offering to repair units, to updating their specification sheets, to insistence that the products were actually functioning as intended. The next set of tests were designed to ensure that the sensors would survive the space environment. Only those sensors that were not built/rated for the space environment were the focus of these tests. The driving considerations for designing these tests were realism, cost, and lead time. Temperature was tested with a TestEquity Model 107 thermal chamber, where the units were cycled between -44 C and 70 C and operated at the ends of the range. Vacuum survivability (not operability) was tested with a standard epoxy outgassing-type vacuum chamber. Vibration survivability was tested by random (to 9 GRMS) and sine vibration in all sensor axes at the Energy Systems Test Area at JSC. Finally, for all optical sensors, a blinding test was performed where the units were pointed vertically outside for five hours surrounding midday on as cloud-free of a day as the project could wait for.

For the thermal tests, the test was successful if the units operated within their advertised specifications after soaking at each end of the range. This was not done for the IMUs as GSFC's considerable testing on these units was leveraged. For the vacuum tests, the test was successful if the unit operated within their advertised specification after being under vacuum for at least 24 hours. The level of vacuum is somewhat uncertain as only a coarse vacuum gauge was used for most of the project. 'Full vacuum' was defined as when the gauge was bottomed out at -30 psig. For the vibration test, the units were operated after vibration on each axis. The test was considered successful if the units operated within their specification after each axis and at the end of the axis set. For the blinding test, the test was successful is the units showed no obvious degradation to their pixel arrays or photodiodes.

In order to downselect the remaining LRFs, it was necessary to test their performance on a somewhat flight-like target at flight-like ranges in challenging lighting conditions. Given the schedule and budget, this resulted in the flight-like target being scrap metal sheets screwed to a form that approximated the curvature of the Cygnus Pressurized Cargo Module which was then mounted to a cart. The LRFs were fixed to a COTS telescope tripod that offered fine motion control, as shown in Figure 4. The cart was moved to pre-measured distances and the outputs of the LRFs were compared to the true value. The results of this test, the thermal testing, and the perceived heritage of the unit lead to the selection of the DLEM-SR.

Figure 4. LRF downselect field testing

SOFTWARE ARCHITECTURE

To quickly enable GNC and FSW development, the Seeker project used the CFS FSW architecture and the Trick simulation environment. CFS was developed by GSFC and has heritage from multiple flight projects including the James Webb Space Telescope, the Deep Space Climate Observatory, and the Solar Dynamics Observatory.* CFS provides many essential functions which are common across spacecraft, and supports a framework of modular, reusable applications, tying them all together with a publish-subscribe architecture. This framework allows GNC team members to develop their applications from templates, offering "plug and play" integration to the rest of the FSW, enabling developers to focus on their domain. This architecture is often depicted in what is called a "bubble" or "lollipop" chart, as shown in Figure 5. GNC-specific applications are depicted in yellow.

* https://cfs.gsfc.nasa.gov/cFS-OviewBGSlideDeck-ExportControl-Final.pdf

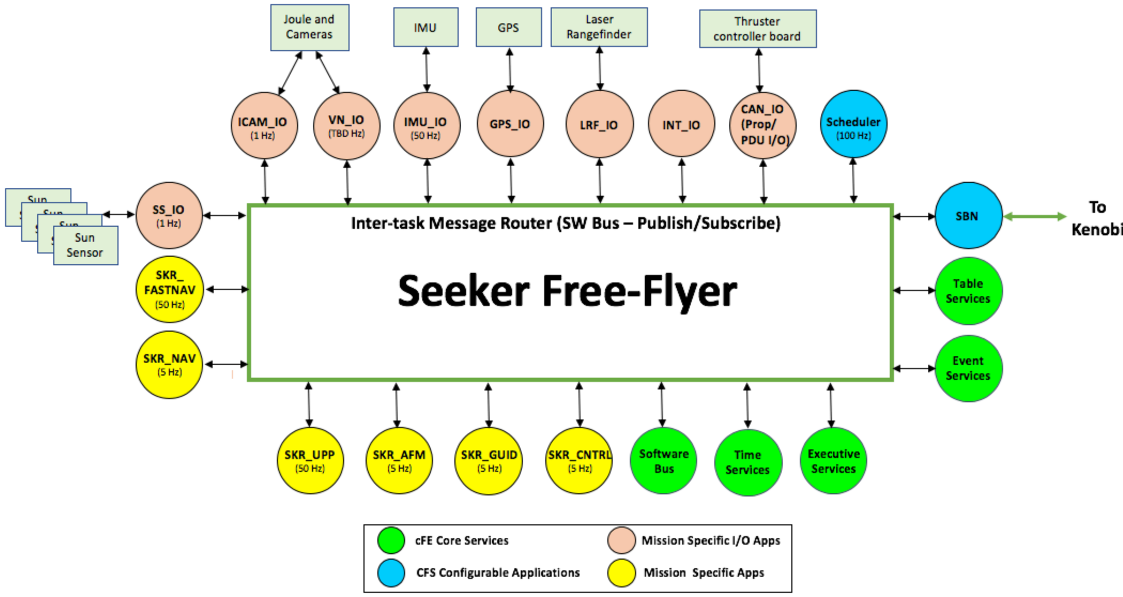

Figure 5. Seeker CFS bubble chart

Trick is an open-source physics-based simulation environment developed at JSC and used for many in-house projects, including the Shuttle Remote Manipulator System, Systems Engineering Simulator, and Morpheus.* Trick is very familiar to engineers at JSC, simple to run, and has many capabilities and tools like 3D graphics and Monte Carlo. Another Trick tool known as TrickCFS allows Trick-based simulations to drive CFS FSW instantiations faster than real-time, which greatly accelerates development.

DEVELOPING THE SEEKER GNC SYSTEM

The adoption of the CFS architecture enabled the separate GNC domains to develop in parallel and the co-location of the team within the Seeker lab environment facilitated rapid communication of issues between subsystems. Additionally, the use a common template for the top-layer of each GNC FSW application enabled team members to draw off each other's experience, enabling the separate subsystems to quickly resolve issues related to the publish-subscribe architecture and ensure each domain had all the data necessary from the dependent subsystem.

Navigation Filter Development

In the early phase of algorithm development, two competing possibilities for a navigation architecture were considered. The first option was a purely kinematic filter, absent any knowledge of an inertial reference frame, which would only attempt to determine the relative state to Cygnus and rely on Clohessey-Wiltshire (CW) propagation for the dynamics model. The second option was an inertial navigation filter containing the Seeker inertial state and either the Cygnus inertial state (Dual-Inertial Filter, or DIF) or the relative state to Cygnus (Inertial-Relative Filter, or IRF).

While the kinematic filter initially held promise, several challenges arose. First, the reliance on CW dynamics would require a re-design for any follow-on mission beyond a circular LEO orbit, and required assumptions about both deployment altitude and direction. More critically, without

* https://github.com/nasa/trick

an inertial reference frame and in the absence of a pose measurement, there was no way to compensate for the gyro drift in the filter. For these reasons, an inertial navigation filter was selected as the path forward. A DIF and an IRF are mathematically equivalent formulations, the primary difference being the location of the complexity in the filter. In a DIF, the dynamics model is relatively straightforward, but the measurement models and partial derivatives are more complex, particularly for relative measurements. Conversely, in an IRF the dynamics model requires additional complexity, but the measurement models are simpler. The Seeker GNC team opted for the IRF paradigm given the majority of the measurements would come from relative sensors.

The navigation system design leveraged an architecture used by Project Morpheus. An IMU Preprocessor application (IMUPre) from that project was adopted and used to downsample the raw IMU data, perform coning and sculling corrections, and publish the data in both a common inertial reference frame and a vehicle body frame. The navigation subsystem was split into a high-rate fast propagator (FASTNAV), operating at 50 Hz, and a low-rate filter (NAV), which operated at 5 Hz. FASTNAV performed state integration, computed dynamics partials, and applied the Kalman Filter updates. NAV calculated the measurement updates to the filter state vector.

Vision-Based Navigation (VizNav) Development and Testing

As mentioned above, a parallel approach was selected for the vision-based bearing measurement, referred to as VizNav. Due to limited resources, the combination traditional and neural network approach was contracted out to the Aerospace Engineering department at University of Texas at Austin (UT). The neural network-only approach was pursued internally at a low level. To reduce development risk, Seeker project management identified a third approach to pursue for visual navigation. This was a purely traditional approach (built around SIFT) contracted out to a nearby company.

The internal approach and the UT approach were both initiated in Q4 CY 2017. The purely-traditional third approach was initiated just before the end of CY 2017. As development proceeded and scope was refined, the UT team was also tasked with developing the interface from the algorithm to the FSW. The UT team created several internal teams, responsible for various aspects which could work in parallel. The work was completed at UT, with several in-person meetings throughout the development process to reconcile schedules and interfaces. The developer responsible for the SIFT approach was physically co-located in the Seeker lab. By the end of Q1 2018, it became clear that there were insufficient resources to continue the internal development of the neural network-only approach and its development was halted. The remaining two approaches were delivered midway through CY 2018 to be integrated with the Seeker FSW.

A test series was devised to evaluate both approaches in both flight-like and enveloping scenarios. To accelerate test development, the Orion Camera In the Loop Optical Testbed was used as a basis for the creation of a similar testbed. A series of real and synthetic images and videos were selected, both with and without Cygnus Enhanced vehicles in the frame with various backgrounds, lighting conditions, colors, etc. These were displayed on a 4k screen with a flight-like camera and lens combination set up so that the screen filled the camera's field of view. Ambient lighting from the room was mitigated with a pop-up canopy and a black curtain.

After several days of testing in August 2018, it was clear that the UT approach was far more successful at providing a bearing to the Cygnus vehicle. It should be noted that it is extraordinarily difficult to perform realistic testing of vision-based navigation systems intended for use in space on the ground. There were many differences between the ground test setup and what will likely be encountered in flight, and many other limitations of the test setup (e.g. lower monitor resolution than twice the camera resolution). With that understood, it was the robustness of UT's approach and the uncertainties regarding the flight imagery coupled with the sensitivity of SIFT features, which were the core of the other approach, that lead to the project's selection of the UT approach for flight.

Guidance Development

Seeker's guidance algorithm was originally envisioned to make use of a potential field method for waypoint seeking and hazard avoidance. In general, potential field methods generate a force as a function of position within an artificial potential field, which drives the spacecraft toward low potential areas (waypoints) and away from high potential areas (hazards, or keep-out zones). Due to the project timeline constraints and final sensor selections, this approach was replaced in favor of a simplified, yet equally capable approach to translational waypoint seeking. This approach generates a velocity command as a function of distance to the waypoint. The velocity command is always in the direction of the waypoint. It has a constant magnitude if Seeker is further than an iLoaded stopping distance to the waypoint, and a linearly decreasing magnitude as Seeker approaches the waypoint within the iLoaded stopping distance. The result is effectively an outer loop controller that upper-bounds Seeker's kinetic energy. Target tracking and attitude waypoint logic was implemented to point Seeker's rangefinder and navigation camera at Cygnus and demonstrate attitude control. In target tracking mode the desired attitude is generated as a function of Seeker's position relative to Cygnus, while in attitude waypoint mode the desired attitude is provided by the Automated Flight Manager (AFM). The rotation between the current and the desired attitude is converted to Euler angles, which are passed to a phase plane control algorithm.

Though potential field guidance was not implemented, the necessity for a hazard avoidance capability remained. To accomplish this, guidance simply ignores position waypoints that would drive seeker into or through a hazardous area (represented by an iLoaded keep-out zone). In the future, as Seeker's situational and environmental awareness increase, these keep-out zones will be generated in real time.

The selection of a simplified waypoint seeking and hazard avoidance method resulted in rapid implementation, and simplified testing and debugging of the guidance algorithm in the integrated Trick-CFS simulation environment. Additionally, the simplified approach is general enough to accommodate future implementation of potential field based guidance without major code or algorithm re-design.

Control Development

The Seeker control algorithms were designed to meet the mission objectives and constraints. A proportional-integral-derivative controller was designed to calculate the thruster duty cycle from the current velocity error. The derivative gain is zeroed since the Seeker vehicle sensors do not accurately measure acceleration. The integral term is limited to prevent command saturation. The control gains, integral limit, minimum firing time, and firing time increment are inputs into the control system that can be updated throughout the mission. Similarly, a phase plane controller was designed to calculate the thruster duty cycle from the current attitude and attitude rate errors. Thruster firings are commanded when the attitude and rate error exceed given limits, and the thruster duty cycle increases linearly with rate error. If the attitude error exceeds the maneuver limit, a maneuver is commanded until the error falls within the phase plane. The phase plane limits and firing time increment are inputs into the control system that can be updated throughout the mission. For both algorithms, the thruster duty cycle is converted to firing time per thruster and added to the final firing command.

The translational and rotational control algorithms were developed and analyzed in Simulink before being implemented in the flight software. The models include the guidance logic to calculate the velocity and attitude rate error, as well as simple propulsion and navigation models. The models allowed for rapid development and closed-loop analysis of the Seeker control system while the simulation environment was being developed. The algorithms were further tuned in the flight software after integrated vehicle testing.

Automated Tuning, Verification and Analysis

Initial values for many of the navigation filter's Gauss-Markov parameters were chosen based on the sensor specifications and using engineering judgement. Unfortunately, the Trick simulation Monte Carlo capability became available very late in the project, which, when compounded by personnel constraints, required a more automated approach to be taken for the filter tuning process. The development cycle simply could not afford to spend days or weeks manually varying the navigation tuning parameters and running Monte Carlo sets to evaluate the effects of the changes.

In order to further accelerate filter tuning efforts, a brute force approach that leveraged Trick's Monte Carlo capability was developed. This capability, colloquially referred to as the Tuning Bulldozer, allowed for individual filter parameters to be varied across a broad range of values in an entirely automated way. The resulting output was viewed in the Koviz plotting tool, which allows users to sort the plotted lines by the magnitude of the dispersed value. This allowed for trends to become obvious, less sensitive parameters to be ignored, and optimal values to be selected for certain parameters as a baseline for additional manual tuning efforts. The Tuning Bulldozer was capable of analyzing 100 values for a filter tuning parameter within about an hour, which would take an analyst more than a day to do manually. That comparison assumes the analyst would cover the exact same values as the Tuning Bulldozer, which an experienced analyst would deem unnecessary. The automated approach also allowed the navigation engineer to specify approximate ranges for different parameters, allowing GNC engineers to run the Monte Carlo analysis in the background while working their own tasks. This method was used to determine the order of magnitude for the vehicle dynamics process noise Power Spectral Density values, along with testing the time constants and steady-state standard deviation values for the filter Gauss-Markov parameters.

The project also leveraged another internal JSC tool, called VERAS, which has the capability to load Trick simulation data, parse the data, compare it to requirements, and generate PDF reports of which requirements were (or were not) met. Once the Tuning Bulldozer had refined the list of tuning options to the highest-impact parameters and bounded the ranges of potential values, project engineers could manually run Monte Carlo analysis in a more traditional approach, using the VERAS tool to quickly evaluate the effects on navigation performance, propellant usage, and mission time and determine a set of parameters which should provide robust performance while allowing Seeker to achieve full mission success.

HARDWARE/SOFTWARE INTEGRATION (HSI) MILESTONES

In order to accelerate overall project development, a series of HSI milestones were created. These milestones required increasingly advanced levels of system development and integration, creating a forcing function for the development schedule. Three were initially planned, but by the end of the project four had been completed.

The first HSI was intended to demonstrate basic functionality of the AFM, camera input/output (I/O), navigation propagator, basic functionality of flight control, and basic functionality of the propulsion controller with a target date of February 2018. This test drove the development of the simulation and FSW environment to the point where they could be used together for the first time. It also drove the development of the hardware-in-the-loop testbed. Not all of the subsystems achieved their goals for this milestone (GNC did, for the record), but completing every subsystem goal was inconsequential to the overall project schedule as the purpose of the milestone was to drive project progress, making it a success.

The second HSI was intended to demonstrate all the capability required to fly the mission profile through the attitude maneuvers. This required the development of guidance, the Kalman filter, integration of GNC, increased AFM capability, increased flight control capability, sensor interfaces, ground commanding, and more by April 2018. Again, not all of the subsystems achieved their goals for this milestone. A number of integration challenges were identified and were moved to a new HSI milestone. As this milestone again drove significant development, but because a number of key goals were missed, it was considered by the project to be a partial success.

The third HSI test (known as HSI 2.5) was intended to bridge the gap between the prior HSI and the next (in which all of the vehicle capabilities would be demonstrated) by July 2018. The GNC team was hoping to execute the test with the entire suite of hardware sensors (no sensors simulated), but were unable to overcome the challenges of testing with terrestrial accelerometers in a lab environment within the timeframe of the test. Additionally, the vision-based navigation system was not yet integrated. The milestone was changed to allow for simulated sensors and all subsystems met their goals. This drove the development of the ground command architecture, various GNC upgrades, the propulsion controller, and more. The project considered this milestone to have been successfully met.

The fourth and final HSI test (known as HSI 3) was intended to demonstrate all of the capability that we would demonstrate in flight with simulated (but realistically modeled) sensors by September 2018. This drove the integration of the VizNav system, the tuning of the Kalman filter, the overall development of the GNC system into its flight state, and more. During the test campaign for this milestone, the actual hardware for the relative navigation system was used in place of the simulated sensors. As all subsystems met their goals for this milestone and now were demonstrated to be functioning in a flight configuration, the project considered it a success.

The HSI milestone approach provided multiple benefits to the project. This included early deadlines which required the subsystems to work on interfaces, both with the hardware and with each other, early in the development cycle. Periodically re-integrating with the hardware frequently revealed issues with recent development work which were not apparent in simulation. Running the algorithms with the hardware uncovered CFS scheduler issues related to running with multiple processor cores along with application timing issues, allowing them to be debugged before final integration.

The Rendezvous Operation Sensor and Imagery Evaluator (ROSIE) Testbed

ROSIE, shown in Figure 6, is a 6 DOF robotic motion platform that is able to replicate typical relative motion between target and chaser spacecraft performing proximity operations. The platform can support payloads 12 in. by 12 in. by 18 in. and weighing up to 40 lbs. ROSIE has a hexagonal base that is driven by three omni wheels offset by 120 deg. It also has a 2 DOF rotational platform mounted on screws to support vertical motion. In its body frame, ROSIE has unlimited travel in the X and Y directions at up to approximately 0.22 m/s, unlimited yaw up to approximately 30 deg/s, +/- 9 degree roll and pitch at up to 1 deg/s, and 0.75 m of vertical travel at up to 0.03 m/s. ROSIE can be driven by scripts, a hand controller, or the Trick simulation.

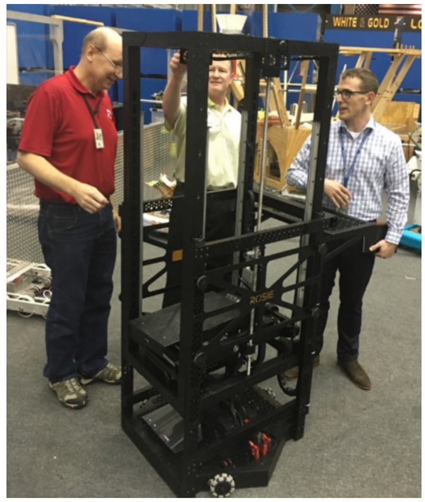

Figure 6. The ROSIE testbed at JSC

While ROSIE was designed to support sensor payloads, Seeker's overall small size and mass meant that the entirety of the prototype spacecraft breadboard (also known as a flat sat) could fit on the motion platform. The Seeker team developed the interface between Trick simulations and ROSIE, allowing the Seeker Trick-based simulation to drive the motion platform. This created a quickly reconfigurable testbed that allowed for hardware-in-the-loop testing. The FSW and simulation architectures allowed for the selection of various combination of real and simulated sensors and effectors, allowing many combinations to be tried in succession and rapid troubleshooting of problematic units. Testing typically was done in a large, open space with a fairly flat floor (waxed tile or low-pile carpet). Testing started with a completely scripted version of Seeker's expected motion, verifying ROSIE was functioning as expected and providing a baseline for the platform's motion. The system was then reconfigured to be driven by the Trick simulation with inputs from the Seeker GNC FSW and all sensor inputs simulated. This verified the connection between the simulation and ROSIE. Various hardware sensors could then be enabled and tested.

CONCLUSIONS

The Seeker 3U CubeSat development effort presented many challenges to the GNC team, the compressed schedule required trade studies, hardware procurement, algorithm development, testing, and integration to be completed within just over a year. To accomplish this feat, the GNC team rapidly downselected a sensor package, found ways to quickly test and attempt to qualify the sensors, developed the software, integrated with hardware, and tuned the system to complete a difficult mission with finite resources.

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REFERENCES

[1] J. Wagenknecht, Et al., "Design, Development and Testing of the Miniature Autonomous Extravehicular Robotic Camera (Mini AERCam) Guidance, Navigation, and Control System." *26th AAS Guidance and Control Conference*, 2003