Autonomous Systems Validation (SysVal) environment for advancing Mission Operations

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ABSTRACT

In order to maintain the health and productivity of satellites, it is crucial to develop a system that can swiftly, accurately, and effectively reproduce the on-orbit workflow and behavior a spacecraft experiences. To achieve this, Planet created the Systems Validation (SysVal) ecosystem; originally developed to validate individual spacecraft subsystem design requirements, and has evolved to encompass satellite concept of operation workflows, innovating test processes while mitigating risks through the ability to rapidly mimic on-orbit activities in a lab environment. SysVal is a fully integrated hardware and software system composed of a ground station network and a mission operations center with multiple integrated satellites, developed in-house by Planet, to assist with operating its Dove constellation of Earth-imaging satellites. Planet's implementation of agile aerospace has exposed the value of SysVal, which facilitates seamless transitions of operational improvements from development and experimentation to rapid productionalization by incorporating "Test-Like-You-Fly" principles. SysVal utilizes cloned instances of Planet's operational mission control interfaces and data storage platforms along with fully integrated flight capable satellite hardware, the same build that is flown in space, to test software upgrades before they are deployed on-orbit, reproduce on-orbit issues on the ground, replicate continuous "Day in the Life" satellite operations, examine changes with potential operational impacts, while being easily managed remotely by a distributed team. System autonomy is a principal component of SysVal to alleviate human-in-the-loop decision making, maintenance and resources, and is utilized for quick snapshots of the testbed states, software deploys to match the lab environment to the production environment, automated flashing of lab satellite onboard software images to match on-orbit satellites, as well as autonomous analysis of system-level metrics and daily testbed testing with operator notification. This paper describes the SysVal system utilized by Planet and the latest automations integrated into the ecosystem that assist with the testing and development of operating the world's largest Earth Observation satellite constellation.

INTRODUCTION

Planet operates the world's largest Earth Observation satellite constellation, with hundreds of satellites producing daily coverage of the entire Earth's landmass. From early on, Planet has embraced hands-on testing and rapid iteration to drive innovation in its spacecraft development. This also holds true for Planet's operational needs; our agile aerospace philosophy drives technologies and techniques to maintain the health and safety of the fleet, enable quick diagnosis and root cause analysis of on-orbit anomalies, and facilitate rapid iteration of critical mission services with minimal operational downtime or customer impact [1]. A core component of Planet's agile aerospace tool suite is the Systems Validation (SysVal) ecosystem, an innovative satellite testbed. SysVal is a fully integrated end-to-end system encompassing all critical paths utilized in Mission Operations. At Planet, a satellite operator's role encompasses maintaining nominal operations, triaging and resolving anomalies, performing on-orbit experiments, as well as the testing of new software releases on the ground and on-orbit. Operators write code to develop and maintain automation tools as well as create satellite metrics to monitor the health of the fleet. SysVal's purpose is to provide an operations environment representative of what is used for on-orbit satellites. It is a one-to-one parity of infrastructure used by the satellite operations team to enable quick evaluation and analysis of operational impacts to the integrated system. SysVal enables operators to create, deploy, and test software, explore operational experiments and evaluate new techniques to investigate satellite behavior. It provides the environment that helps facilitate the maintenance of and increases the capabilities of, our satellites. Through performing system integration tests which execute end-to-end tests that validate performance in a flight-like scenario, operators can quickly gain

confidence that changes to software, experiments, or anomaly investigative actions will not adversely impact customers, operator workload, automation tools or health metrics which monitor the state of the fleet. The remainder of this paper is structured as follows: First, to fully grasp the scope of SyVal's impact and the driving influence behind the various automations developed to maintain and facilitate Planets Mission Operations, an overview of the system architecture and SysVal origins is reviewed. SysVal's Use Cases are then detailed, followed by the automations utilized, followed by an analysis of the impact of SysVal on the satellite operations workflow at Planet.

SYSTEM ARCHITECTURE

At Planet, System Validation is used to improve quality and drive development speed with a test infrastructure where operators can try new hardware designs with Missions operational software. The architecture of the SysVal Ecosystem has been molded over time with the following ideologies:

1. System tests should be automated,
2. Continuous integration and deployment of hardware and software changes is embraced,
3. System tests do not need to cover everything, but they do need to be explicit about what they cover,
4. Automated system tests and reporting enables "continuous validation",
5. Parity with orbital hardware and production mission services is key to enabling, Test-Like-You-Fly principles, and
6. Users should interact with System Validation as you would interact with an on-orbit satellite.

The SysVal ecosystem is composed of numerous components, utilizing flight or production capable hardware and software services wherever possible to achieve parity with on-orbit production. The test venues are a product of cross-team cooperation to build and maintain production-level ground station servers, test equipment, satellite test units and flight-quality satellites. Currently, SysVal encompasses seven in-house ground stations, three fully-integrated Dove-generation satellites and four fully-integrated SuperDove-generation satellites. The software suite implemented by SysVal focuses on automating operator actions and analysis and is defined by the following key concepts:

- Test Scenario - a "playbook" of an operation scenario used to collect data for tests,
- Test Suite - A group of related test cases that run after a scenario. These are the high-level test results of interest to report at release reviews,
- Test Case - An individual test case run on the results of a test scenario. An example might be "Ensure the satellite radio time is synchronized". These are narrow in scope and should map up to functional requirements, and
- Test Venue - A group of hardware used to run a test scenario consisting of a ground station and satellite.

The software suite executes test scenarios to validate new versions of Operational Software (satellite operator scripts, ground station software deploys, Mission Control (MC) and MC-component deploys), as well as testing new hardware and onboard software. Users can make use of existing testing scenarios or write their own. Figure 1 illustrates a system-level diagram of the SysVal architecture:

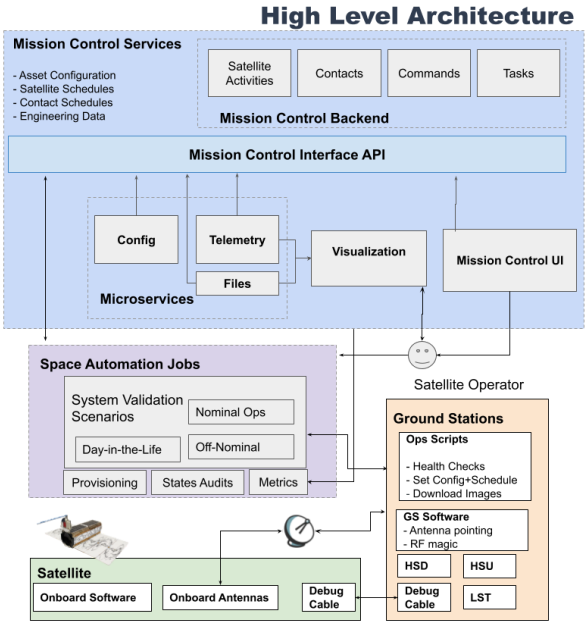

Figure 1: SysVal System Architecture

Background: A Brief History of System Validation

The SysVal ecosystem and its capabilities organically grew at Planet based on the needs to achieve the Medium-Resolution Missions objectives. Over time, there have been three major needs/phases that drove the development design and utilization of Sysval. These three needs represent phases in SysVal's history: first, initially used for rapid development, second, focusing on automated validation and continuous integration, and finally, focusing on satellite operations anomaly investigations, by maintaining parity with production. Each phase did not replace the prior, but rather expanded the purpose and desired functionality of SysVal. With each phase, SysVal's ownership and operational ideologies have grown and evolved.

SysVal was formed to address the need for an accessible development environment of mission-critical services for cross-team collaborative development. Developing a system that actively incorporates all the crucial missions services and software is invaluable. Changing missions services used by SysVal to iterate, build, test, and demonstrate desired interactions rather than exhaustively simulating outputs, allows Planet to release operational systems early and often. The initial ecosystem was introduced and maintained by a systems integration team, whose internal customers were Ground Operations, Missions Software, Onboard Software and Satellite Operations. As such, SysVal has existed with its core components from early stages of the Planet's Medium-Res Mission, and was originally used for rapid development as each critical mission service component was in its own early lifecycle stage. In this phase, SysVal established the concept of a nominal operations scenario (ConOps), an automated code which when executed, would validate that there were no unexpected errors when executing ConOps. The ConOps testing scenario facilitated the quick development of critical infrastructure by internal customers focused on developing operational services into mature stable products. However, this phase faced challenges due to the manual time-consuming interactions. The systems integration team was limited due to the manual tasks of documenting, applying, and confirming the states under test, and SysVal lacked detailed test outputs or explicit mission operations focused testing.

As products and services continued to mature at a swift pace, SysVal directly enabled the maintenance and innovation of Medium-Resolution Missions. The rapid development cycle of mission services underscored the need for incorporating and expanding automated validation and continuous integration and development practices into SysVal. This phase led to an expansion of capabilities defining SysVal as its own entity, greater than the sum of its parts. The transition towards automation led to a decrease in the required time resources from the system integration team members. The phase drove the development of various automations specific to the systems-level interactions found in the SysVal ecosystem by generating code to interface with and set satellite states to known baselines, multiple scenarios scoped to testing specific phases of orbit-operational activities, and automatic daily testing.

As Planet's medium-resolution constellation expanded, Satellite Operations became the primary internal stakeholder of SysVal, and found value in using SysVal as a platform to explore on-orbit experiments, anomaly investigations, and changes to operational workflow. Maintaining parity with production mission services and incorporating flight hardware established the SysVal ecosystem as a valuable asset when developing software in reaction to an urgent on-orbit anomaly or workflow pain points. SysVal enabled operators to execute on-orbit activities, on the ground, and provided transparency into operational workflows and knowledge exchange between teams. During this phase there was an organic transition of ownership from the system integration team to satellite operations, which is where SysVal stands today. The ecosystem now works with the Missions Software and Ground Operations teams to provide consistency with the production environment, and encompasses more testing use cases and automations than ever before.

USE CASES

Replicating the on-orbit environment: Nominal Operations

To fully-describe how SysVal replicates the on-orbit environment and satellite behavior, it is important to understand the nominal operations that run on Planet's Dove and SuperDove satellites. These are the most common activities and contact types that a satellite

executes as a part of its daily operations, and is replicated in SysVal as a means to test that any software upgrades or changes to a satellite's configuration does not negatively impact these events. There are three types of communication radios used by the spacecraft: the UHF Low-Speed Transceiver (LST), S-band High Speed Uplink (HSU) receiver, and an X-band High Speed Downlink (HSD) transmitter.

The concept of a nominal operations scenario in SysVal is an example of Planet's Test-Like-You-Fly principles, because it encompasses the core daily operations tasks that a production satellite runs. The scenario has three main parts: an LST contact, followed by an imaging activity, followed by a Downlink activity with an X-band contact. In general, when running the ConOps SysVal scenario, users are following the outlined testing criteria to confirm a satellite is operating as expected:

- Acquiring imagery,
- Downloading recent imagery,
- Downloading logs,
- Logs show no unexpected errors,
- Telemetry is being ingested,
- Tasks are executing successfully,
- Downlink is performing nominally, and
- Any other performance parameters are being met.

The goal of the ConOps scenario is to be able to quickly test that a satellite's operations have not been negatively affected by any changes. In total, the scenario takes approximately 20 minutes to execute. This is a fast, efficient, and safe way to test without having to risk impact on production satellites, rely on a satellite's orbit and contact availability, and consume ground station resources. The nominal operations scenario also enables operators to have a quick turnaround time from identifying an on-orbit anomaly, to testing a solution on the ground, to deploying the fix to production.

Replicating Anomalies

A key factor in diagnosing, triaging, and ultimately solving a problem is being able to replicate the conditions for which the error occurs. While a seemingly obvious first step, this is a huge challenge when the anomaly one would like to replicate is orbiting Earth. SysVal is utilized by the engineers at Planet to replicate on-orbit issues to accurately and effectively diagnose the on-orbit anomaly a production satellite is experiencing, achieved through several steps. First, any activity that is run by an on-orbit satellite can be run by a lab-based satellite through the cloned production instance of Mission Control on SysVal. Users can directly log onto the lab satellites to monitor spacecraft telemetry and logging as they execute activities and run multiple sequential activities without having to worry about the many limitations these types of tests have in space. Limitations include (but are not limited to):

1. Maximum power draw: in space, the Dove and SuperDove satellites move between sunlight and eclipse, thereby limiting their capacity to run many consecutive activities without reaching critical power levels. In SysVal, operators can circumvent this limitation because of the continuous power supply the lab satellites are equipped with,
2. Ground station contact availability: though Planet has a global network of 48 ground station antennas to enable activities to be scheduled onboard production satellites, there are hundreds of satellites in competition for ground station resources. Relying on ground station contact availability could extend a test that could take 20-40 minutes on the ground, to several hours in space, and
3. Impact to satellite productivity: utilizing lab satellites for initial testing ensures that if there are issues, this does not impact production satellites and coverage quotas

Software Development

One of the main uses of SysVal is software and firmware development and testing. It is critical to test all proposed software changes on the ground prior to making any changes to on-orbit satellites. In general, the workflow for SysVal software development is as follows:

1. The Flight Software Team (FSW) releases a new software version to be tested
2. A new central processing unit (CPU) package is created and upgraded on a SysVal lab satellite
3. Nominal concept of operations is run on the lab satellite to replicate the operations of a part of a production satellite's day-to-day tasks, and ensure the software upgrade is performing as expected

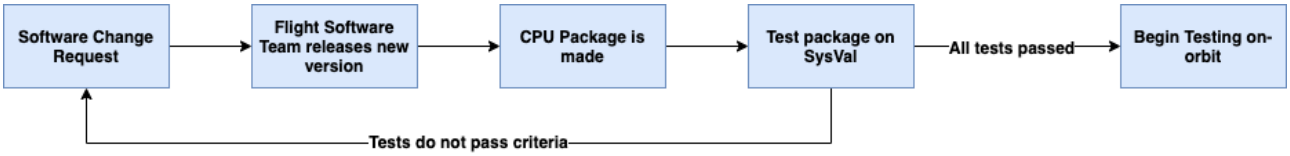

Figure 2: SysVal Software Development Workflow

4. The testing acceptance criteria is evaluated and, once accepted, the package is then upgraded onto staging satellites for on-orbit testing

Fully testing a new software package can be done in only a few short hours before upgrading to on-orbit satellites. Figure 2 summarizes the SysVal software development workflow.

Day in the Life (DITL) Testing

The Day In The Life (DITL) testing scenario is designed such that a lab satellite will follow the identical schedule of a specified on-orbit satellite. The purpose is to test continuous nominal operations of a satellite. The DITL scenario is particularly important in testing significant software changes that require monitoring a satellite over several days before approving the upgrade to go to on-orbit satellites, and for attempting to replicate idiosyncratic on-orbit satellite anomalies.

A distinct feature of the DITL scenario is the Solar Array Simulator (SAS). The purpose of the SAS is to mimic the power state of an on-orbit satellite in a lab environment to within a 5% margin of error. The performance of the power subsystem on a satellite directly impacts all other subsystems. Therefore, it is of particular importance to test activities that require a significant power draw, to ensure that if this is run on-orbit, satellites will not be put into a low power state that could cause it to brownout, potentially damaging onboard components.

AUTOMATIONS FOR EASE

A core component of SysVal is the automations that have been developed to streamline the testing process. The following section details the different tools that have been developed over SysVal's lifetime to assist with test and experimentation.

State Machine Audits

A system-wide audit of the SysVal testbed state is run twice daily to ensure operators have a clear picture of the system configuration prior to beginning tests. Because the majority of the Planet team is divided into two time zones, Pacific Standard Time for the San Francisco users and Central European Time for the Berlin users, the audit is run at the beginning of the San Francisco day/end of Berlin day and the beginning of the Berlin day/end of San Francisco day. Daily audits are a necessary component to SysVal because there are many users for a single testbed that require different configurations for each unique test. State machine audits are done for both the lab satellites and ground stations a part of SysVal, and the results of the audits are automatically shared to the operators via internal direct message. As a part of the audit system, hardware IDs that are out-of-family are highlighted, which brings transparency to the overall state of SysVal, and ensures that software upgrades and deployments are correctly done across the SysVal components.

Software Deploys

To decrease the number of human-in-the-loop actions required on SysVal, an optional follow-on process to the State Machine Audit was developed. If variations between the production baseline environment and the SysVal environment are detected for the ground stations or satellites, an automatic deployment of the current production configurations is kicked-off. For ground stations this action occurs weekly, outside of normal business hours. Deployments of operation code occur daily after the audits, and satellite software is fully provisioned once a month. A particular functionality of this automation is the ability to specify the hardware of interest to exclude from automated deploys and updates, such that multiple SysVal users can concurrently test different configurations without interfering with one another.

Metrics

SysVal incorporates metrics reports developed for on-orbit satellite operations to gain detailed insight into the ecosystem's health. The reports are an aggregation of various data sources from telemetry, satellite task outputs, activities, onboard log, and historical configurations, enabling operators to deeply analyze the

state of each spacecraft. Reports are structured as a collection of records, which are made up of related metrics and metadata. Metrics can help identify satellite failures as well as provide insight into satellite health and productivity. The reports are generated multiple times a day and can be triggered automatically after a SysVal scenario has executed. The results of these reports are presented in various dashboards to simplify SysVal-wide health review and anomaly triage.

Daily Health and Log Rotations

To observe the long-term health and interactions of SysVal hardware, all active satellites execute an automated nominal concept of operations scenario outside of standard business hours. This activity occurs after the State Machine Audits to to act as a heartbeat for the general health of the system. This automation is particularly useful for capturing sudden unexpected hardware or software complications that may not be visible from the State Machine Audit. As a part of the tool, job failures are automatically shared to operators via internal direct message.

Provisioning

The task of integrating a new satellite into SysVal or applying a specific configuration for an existing piece of hardware was a previously very manual process due to the numerous systems involved. Automated Provisioning was developed to take a Dove/SuperDove in any state and have it match a desired on-orbit "buddy" satellite's flight configuration. Provisioning covers the satellite's firmware, onboard software, and configuration settings. The provisioning automation is flexible to allow users to select any combination of configuration settings to match. This automation provides a simple process for the installation of new hardware; the tool will ingest the satellite hardware ID and the desired build version and automatically apply the appropriate configuration to update Mission Control Services. Utilizing this feature has enabled the integration of new hardware and software into SysVal to take less than a few hours to complete.

IMPACT

One of the biggest impacts SysVal has on mission operations at Planet is the reduced latency from on-orbit anomaly identification to deployed solution. In particular to software changes, in less than 24 hours a script can be written, fully tested on the ground via SysVal hardware, tested on-orbit, and deployed to the entire fleet. This type of agile approach to software development in it's application to mission operations is critical to quickly solving any on-orbit software issues that arise, thereby reducing operational downtime of production satellites and mitigating customer impact. Moreover, through the use of SysVal, operators can be confident that the changes have been thoroughly tested and that if the criteria is satisfied on SysVal, it is safe to begin testing and then fully deploy on-orbit.

As mentioned in the *Brief history of System Validation* section, SysVal has evolved from it's initial purpose to better serve the operations team at Planet. The evolution from its initial role of validating individual spacecraft subsystem design requirements transformed with the latest medium-resolution design of the Planet SuperDove; through the use of SysVal, engineers and operators were able to test the concept of operations for the SuperDove generation of satellites prior to launch. This was made possible because of the identical flight hardware used in the SysVal testbed, and the cloned Mission Control interface. Using the same hardware and software tools to test enabled operators to prepare to operate the satellites in space, with little to no difference in the actual concept of operations between lab satellite operation and on-orbit satellite operation, a massive impact to the development of ConOps for the SuperDove fleet.

CONCLUSION

The Systems Validation ecosystem at Planet is an innovative agile aerospace tool developed to assist with the operations of Planet's constellation of Earth-imaging satellites. As described, SysVal provides the ability for users to quickly and rigorously test operation processes while mitigating risks through the ability to rapidly mimic on-orbit activities in a lab environment. Incorporating Test-Like-You-Fly principles into SysVal's infrastructure allows satellite operators and general users to utilize production tool sets without the need to maintain multiple branching copies between the test and production environments. Automations decrease the requirement for personnel hours needed to maintain multiple resources and ensure that users have a clear picture of the state of their testbed at all times. SysVal has a massive impact on Planet's ability to rapidly test and develop software changes safely and efficiently, and has been an integral tool in the development of the medium-resolution generation of SuperDoves.

REFERENCES

1. Doan, D., Flores-Pozo, K., Mankar, A., and Mcgill, L., "Agile Aerospace: Lessons Learned from Planet Mission Operations", Proceedings of the 16th International Conference on Space Operations, Cape Town, South Africa, 2021.