A NEEDED EVOLUTION IN AUTOMATED SATELLITE TESTING

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Abstract – This paper proposes a needed evolution in automated satellite testing for both government and commercial mission applications. Roles and contributions by the U.S. government, commercial satellite services, the satellite manufacturers, and the automated test industry are discussed. Specific areas with identifiable return on investment are presented as a starting point on a long term path for applying current industrial automation to the satellite test sector.

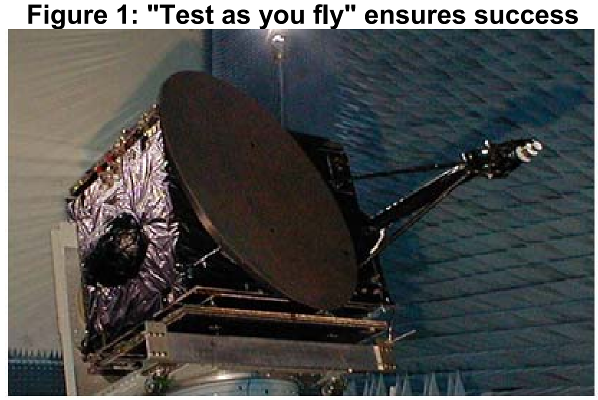
INTRODUCTION

The last two decades have seen a significant growth in information technology and manufacturing automation in U.S. industry, however, limited advancements have been implemented within the satellite integration and test sector [1]. Numerous contributing factors to this situation are discussed in this paper, including the "test as you fly" philosophy, limited satellite command and telemetry data rates, ever-changing satellite designs coupled with limited production rates, the perception of limited or no return-on-investment for the first satellite, aggressive schedule expectations by customers, constrained satellite funding, and aggressive satellite competition strategies. Although ground control stations (GCS) have improved by way of software development efforts, comprehensive test automation has not been implemented in satellites supporting NASA missions, Department of Defense (DoD) technology experiments, and commercial geosynchronous Earth orbit (GEO) communications applications. This paper discusses the present state of satellite testing in these areas and proposes a roadmap aimed at bringing forth an evolution in automated satellite testing through the application of current automated test technology.

SATELLITE TESTING

Presently, the "test as you fly" method, as pictured in Figure 1, is a fundamental tenet of satellite testing and one of the best risk reduction approaches in widespread use today. Unlike terrestrial business sectors (e.g. the automotive

Figure 1: "Test as you fly" ensures success



industry) and with a few notable exceptions (e.g. the Hubble Space Telescope) satellites cannot be repaired once they ascend into orbit. With high costs associated with satellite design and production, which can vary from a few million to hundreds of millions of dollars, and lengthy development schedules, ranging from 2 to 6 years, significant diligence is essential to ensure that the satellite operates successfully once in orbit. By testing with replicas of the mission GCS, the satellite can be assessed as it is flown through mission simulations and with repetitions of functional and performance tests. This strategy greatly increases the satellite's likelihood of success.

Additionally, in development environments that are schedule- and cost-constrained, a "test as you fly" approach often represents the minimum set of test requirements. However, the very nature of this approach is operator-intensive; specifically, it centers the test program around the mission GCS, which primarily serves as a command and telemetry interface. Figure 2 provides a sample telemetry display on which the test validation is based. Generally, a collection of sophisticated

Figure 2: Reliance on GCS telemetry pages results in operator intensive testing

software tools is used to facilitate command sequencing, formatting, and validation as well as telemetry decommutation, display, and limit checks. Several types of pseudo-code [2], such as NASA's Spacecraft Test Operating Language (STOL), are used to provide a test scripting language for repeatable and reliable command sequencing to the satellite and telemetry validations by using user prompts and acknowledgements. Current satellite-testing approaches [3] have exploited this script capability and it is common for scripts to contain thousands of lines of code for just one subsystem functional test and yet still require hours of execution time. Scripts are written for each subsystem's functional and performance testing as provided in Figure 3.

Figure 3: Comprehensive Performance Testing requires significant script development

Attitude Control Subsystem Testing - Hardware Functional Tests - Sensor Calibrations - Phasing Tests - Algorithm Tests
Command & Data Handling Testing - Hardware Functional Tests - Bus Traffic Tests - Flight Computer and Addressing Tests - Data Recording and Playback Tests
Electrical Power Subsystem Testing - Hardware Functional Tests - Power Distribution Tests - Power Regulation Tests - Solar Array Mechanism Tests - Solar Simulation Tests
Flight Software Testing - Modes and States Tests - Autonomy Tests - Memory Tests
Launch & Mission Simulations - End-to-End Tests - Operational Tests - Contingency Tests
Payload Subsystem Testing - Hardware Functional Tests - Performance Tests - Calibrations
Propulsion Subsystem Testing - Hardware Functional Tests - Phasing Tests - Pressure Tests
Telemetry, Tracking and Command Subsystem Testing - Hardware Functional Tests - Performance Tests - Pressure Tests
Thermal Control Subsystem Testing - Hardware Functional Tests - Performance and Balance Tests

A significant contributor to the lengthy test durations that result with the GCS script test approach is the limited command, telemetry, and sampling data rates that are inherent in satellite designs. Command rates typically range from 8 to 2,000 bps, whereas telemetry data rates typically range from 10 to 480,000 bps, depending on Earth or planetary satellite missions and emergency versus nominal operations. With a typical spacecraft comprising 200 separate commands, not including parameters or arguments, and 7,000 telemetry points, with 1,200 being hardware telemetry, an efficient data sampling and commutation scheme needs to be employed. But because of the immense number of command parameter permutations and immense quantity of telemetry points, much of the satellite design can only be checked once with the current script approaches and cannot be trended across the entire satellite environmental test program. As an example, for telemetry points that respond slowly, such as temperature, data sampling for satellite health can be effective at 30-second intervals. Sequential turn-on of heaters via the GCS command link and validation of temperature responses for a satellite with 200 thermistors would require 100 minutes of test time. In addition, a comprehensive thermal-control system test for a GEO communications satellite, which would exercise flight software control of thermal set points, a full thermal-control test routinely can take 12 hours. Because all GEO communications satellites have significant redundancy to meet longevity and reliability requirements, a full thermal control test consumes 24 hours each time it is performed.

Further limitations in applying automation to satellite testing are the continuing satellite design changes and low production rates for a given design. With few exceptions (e.g. the Global Positioning System constellation) satellite missions are one-of-a-kind as can be easily seen in the spacecraft photos of Figures 4 and 5. Mission requirements affect solar array size, battery size and types, power topology and distribution, propulsion types and selection of components, thermal control schemes, deployable types and quantity, and on-board data architectures. There are flight software, commands, and telemetry considerations associated with each mission. Because launch mass also drives the satellite design, the designs trend towards point solutions for each mission with limited reuse design to design. As such, up-front investment in testability and automation is

Figure 4: Earth-orbiting satellites serve high data-rate capabilities

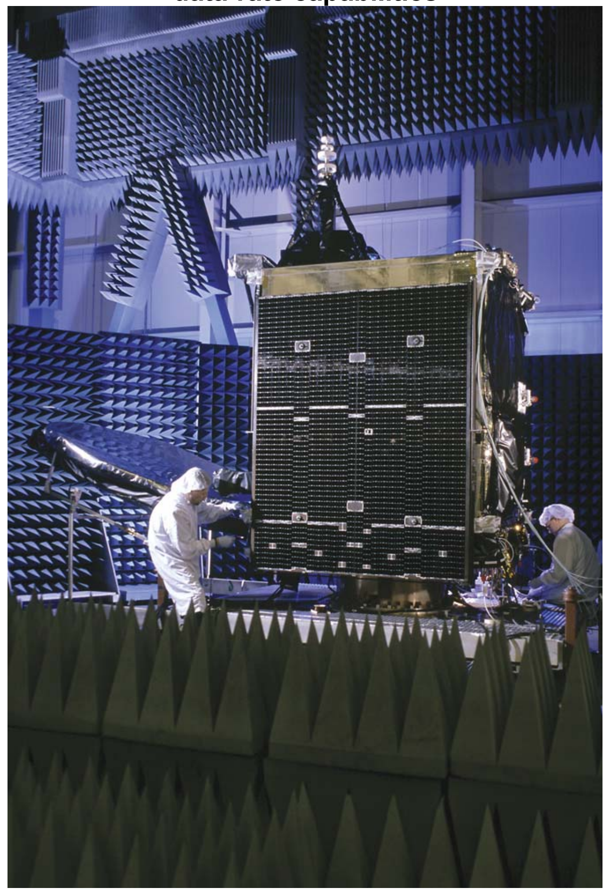


Figure 5: Planetary exploration spacecraft serve unique science requirements

perceived as providing limited return. This perception especially holds true when the design is apt to change significantly for the next mission's requirements. Furthermore, aggressive scheduling and cost expectations by the satellite end users present additional impediments to progress in automation. In the specific case of the competitive commercial market of GEO communications, satellite delivery schedules can be as aggressive as 24 months from contract signature under fixed-price contracts with penalties for late delivery. In the case of NASA exploration missions, which are executed under cost-plus contracts, planetary orbital-alignment conditions can elicit just as much schedule pressure for launch dates. Taking the time to build a test automation infrastructure often gives way to the immediate pressures of a specific mission. Figures 6 and 7 exemplify the test equipment and simple setups that result.

Figure 6: Satellite test setups are point solutions

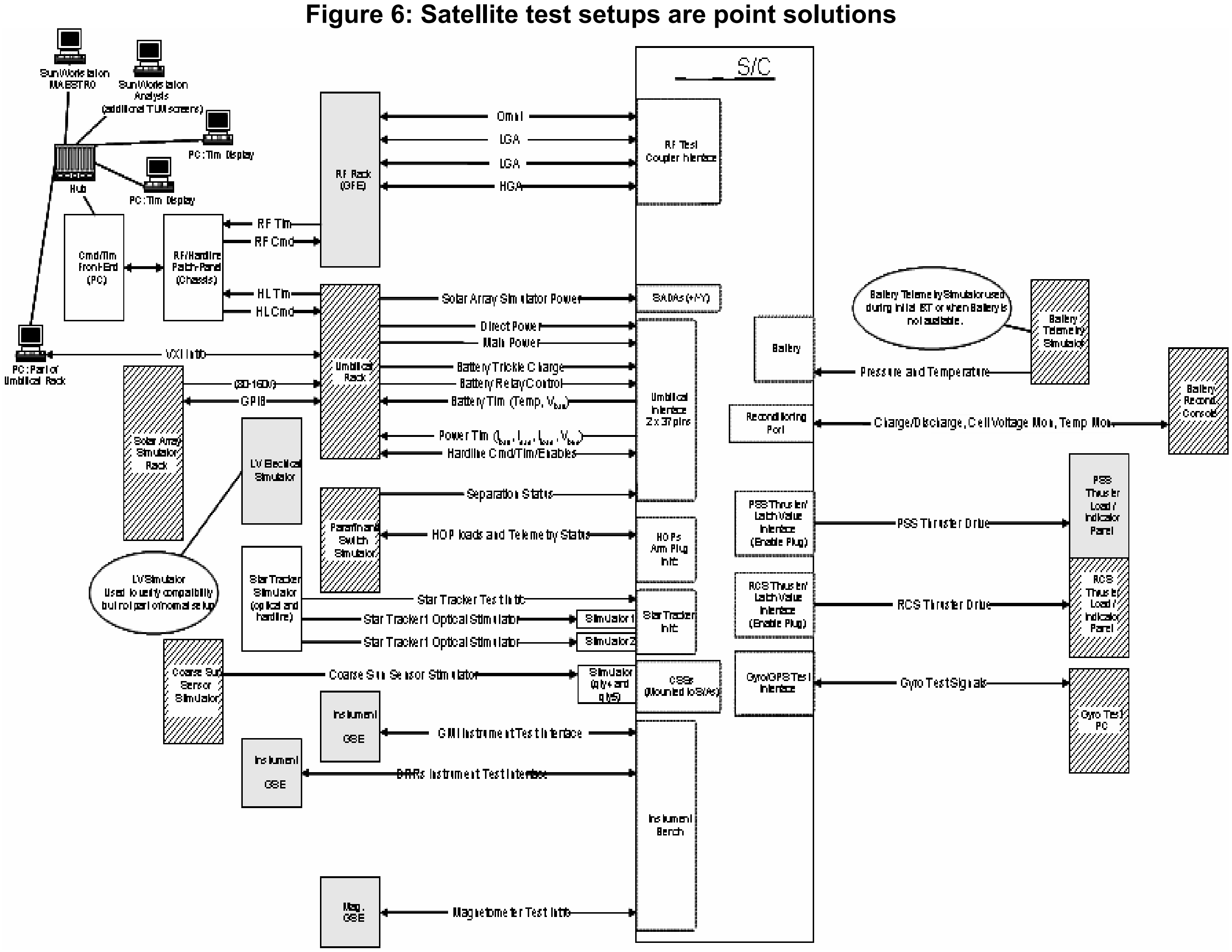


Figure 7: Test automation is limited to basic functions of off-the-shelf equipment

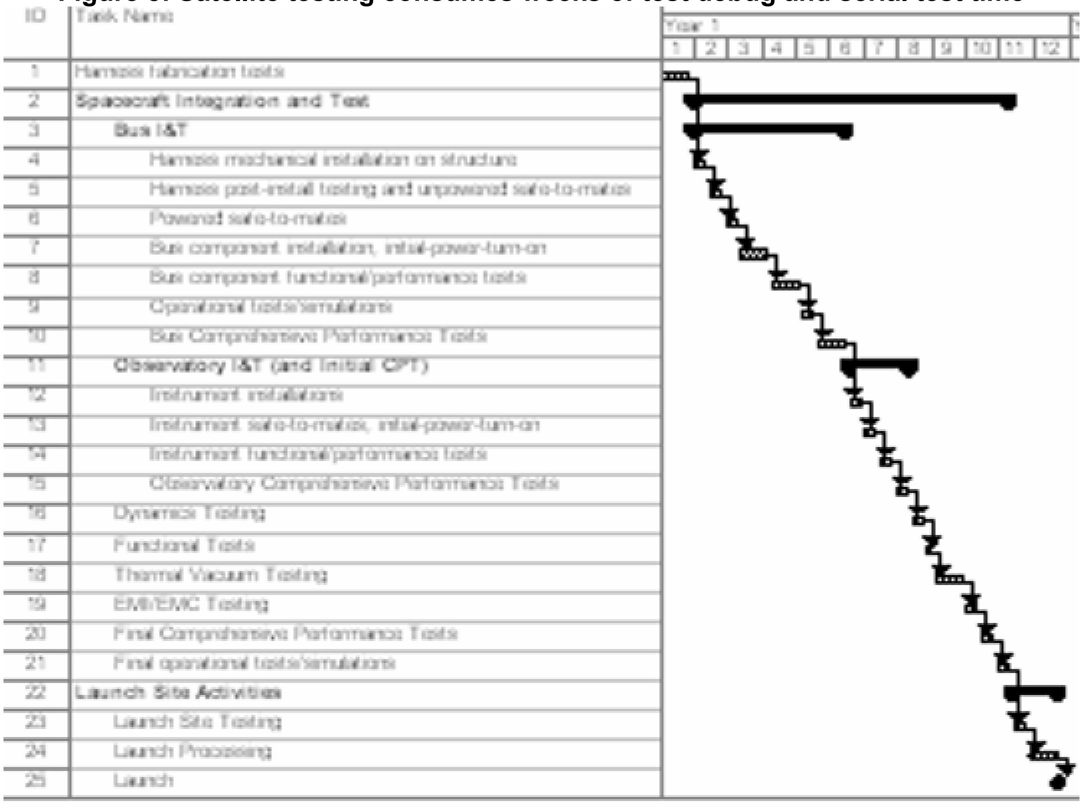
In the satellite business environment then, why push for increased automation? The very nature of the satellite industry necessitates the benefits available from up-to-date automation technology [4]. Test automation provides repeatable, thorough, and comprehensive testing that can be executed more accurately, more quickly, and less expensively than by operators.

Satellites incur high cost, have long development schedules, and must be technically successful because they cannot be refurbished in situ or returned to Earth for repair. Smartly combining automation technology and satellite testing will lead to lower-cost satellites and shorter schedules and better-guaranteed technical success. However, for these claims to be realized, automation technology must be applied across satellite programs in ways that address these previously described limitations. Government agencies, satellite manufacturers, and the automated test equipment industry each have important roles in bringing forth this future evolution.

As mentioned above, the “test as you fly” tenet has led to significant mission success, and there is no substitute for operational mission simulations on the flight hardware and software. Such simulations prove all communication paths and data rates with the satellite, confirm all modes of operation, authenticate the GCS readiness (e.g. telemetry displays, limit checks, alarms, etc), validate command and telemetry databases, validate operational procedures, and train the satellite controllers. In addition, these simulations provide NASA, DoD, and commercial customers (and their insurance providers) confidence that the satellite will be successful. Notwithstanding training of the controllers, which often is performed on high-fidelity software simulators, the mission-simulation testing on the satellite generally requires 4 weeks of testing across a nominal 12-month ground-test cycle as shown in Figure 8. All satellite test programs need to maintain these types of tests in their test programs. Therefore, test automation should be introduced only for the functional health and performance trend tests which generally comprise a longer 12 weeks in cumulative test time. A reasonable objective for automation is a one-third reduction in test time while increasing the comprehensive of testing.

Today, functional and performance tests are executed through the satellite operational command and telemetry paths as an unnecessary extension of the “test as you fly” philosophy or for

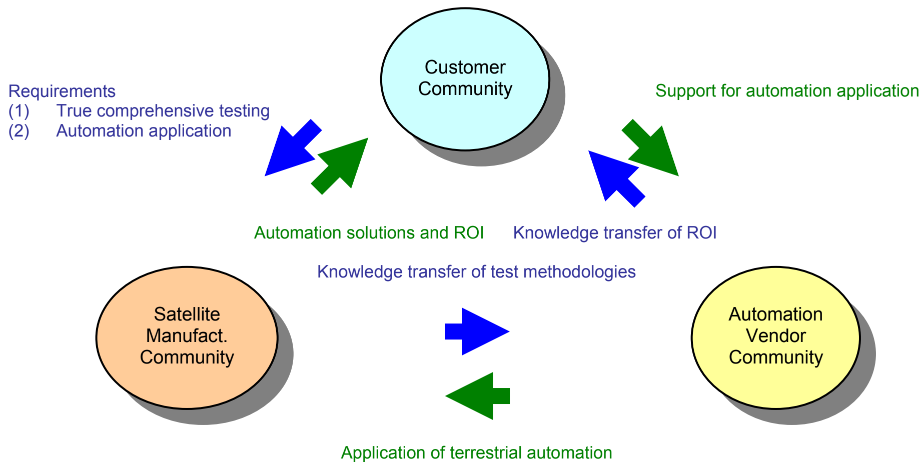
Figure 8: Satellite testing consumes weeks of test debug and serial test time



short-term script convenience. However, such testing results in significantly less-comprehensive testing and trending of the previously mentioned 1,200 hardware telemetry points because of the sheer magnitude of data for the operators and engineers to handle. Thus, the satellite customer community (both government and commercial) needs to acknowledge this detail to be able to serve as a driving force to compel the satellite manufacturers to tackle the appropriate application of test automation. In parallel, the satellite manufacturing community needs to recognize that real return on investments exist in schedule reduction, total staff hours reduction for testing, and thus, total project cost reduction. Additionally, more comprehensive testing is likely to pay off with earlier failure detection and reduction in in-orbit anomalies. These latter benefits provide additional cost reduction, but unfortunately, cannot easily be forecasted until several new programs under a commitment to automation can be evaluated against historical cost data.

Within the satellite manufacturing community, most producers rely on their flight subsystem design engineers to define test requirements and equipment. The approach followed most often is a short-term cost savings through the procurement of limited test equipment and application of simple custom interface designs to meet the specific needs of the satellite. This methodology is counter to those applied in commercial terrestrial industries, which apply an integrated system approach with quality, cost, and schedule emphasis on the testing infrastructure. To bridge the gap between these two approaches, a partnership between the test equipment industry and the satellite manufacturers is the best option as shown in Figure 9.

Figure 9: Triad of automation evolution



Test interfaces for a representative satellite bus shown in Figure 10 include ground power, battery simulators, solar array simulators, thermal stimulators, thruster actuation, and sensor stimulators as well as the front-end communications interfaces of the satellite (i.e. the uplink and downlink). Practical steps along an evolving automation road map are provided for discussion in this paper by the example of three steps, those for increased spacecraft monitoring, more comprehensive testing, and reduced test time.

The provision of ground power is a critical test function and is one of the most fundamental types of test data as shown in Figure 11. Obviously, no tests can be performed without a consistent and reliable source of power. However, current anomaly during the integration and testing process.

satellite test automation generally is limited to scripted power-up and power-down tasks with separate manual operation of ground power supplies or use of simple coded interfaces [5]. Overcurrent, overvoltage, and ramp rate protection in the power supplies also are used. Only recently have electronic strip chart recorders with sufficient sampling rates begun to replace paper recorders. Yet, with the criticality of the ground power and the safety of the satellite, standard practice for monitoring during the integration and test process becomes limited to visual checks by the test operators at initial power up with subsequent monitoring relying completely on satellite telemetry. After the fact, all satellite power diagnostics include a review of the ground power and any input anomalies and most, if not all, satellites have experienced at least one power

Figure 10: Satellite test interfaces exist for automation approaches

Figure 11: Satellite test interfaces exist for automation approaches

Solar array input power, voltage, and current
Solar array power shunting and duty cycle
Bus power, voltage, and current
Bus regulation and efficiency
Battery cell voltage and current
Load voltages and currents
Inrush currents at component turn-on
Power subsystem stability and transients
Hardware critical temperatures

Due to limited data following a test power failure, much fault stress analysis relies on estimates of the ground power behavior because of the lack of integrated data. The application by the vendor power supply community of automation tools that record the ground power input in response to changing satellite loads would greatly enhance the satellite safety. Furthermore, real-time linking of the data with the satellite power telemetry would increase the comprehensiveness of test data review through the use of automation limit checks and statistical trend analysis. With only a few satellite power topologies in existence, this application likely is independent of satellite design, thus providing a clear return on investment.

A further application for power automation would be the routine measurement of component inrush current. The testing approach in practice today is manual; it usually is performed with a breakout box and oscilloscope only at initial power turn-on of the component during its integration with the satellite. With the addition of a current and voltage test monitor on the output of the satellite power distribution, inrush could be captured every time a unit is powered. These data would provide invaluable automated monitoring for the trending of a component's health and the immediate shutdown if any predefined thresholds were exceeded. Power trends often are the first indicator of part degradation and frequently are missed because of the lack of automation.

This recurring data value has long been recognized for monitoring Traveling Wave Tube Amplifier (TWTA) health in ground testing of commercial GEO communication transponder payloads. However, a manual approach often is still the standard practice for looking at TWTA voltage ramps. An existing industry-standard, space-qualified TWTA requires 3 to 5 minutes to power up with manual examination of satellite telemetry. When sequentially performed, which is current operator practice, a 30-transponder satellite, as depicted in Figure 12, consumes more than 2 hours each time the payload is powered for testing. An automated link would enable parallel turn-on with immediate data-checking for safety and data trending. Over the life of ground testing this simple change will save 48 hours of test time. The same TWTAs are used satellite to satellite, so the return on investment would convey across multiple missions.

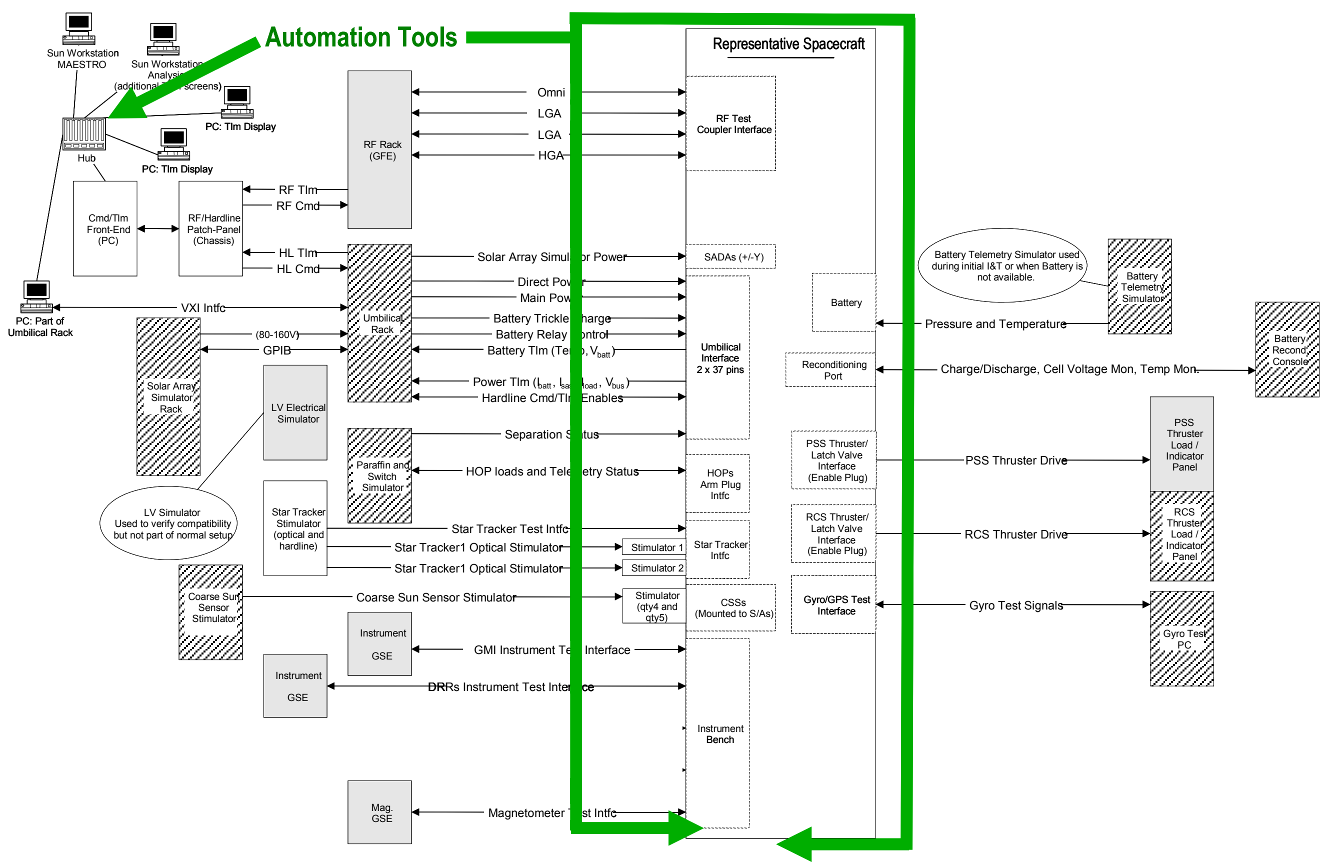
By only applying the "test as you fly" approach, test durations are increased severely due to the low satellite data rates. Mission simulations would provide adequate validation of the satellite uplink and downlink operations, thus allowing the remainder of satellite testing via a higher data rate

Figure 12: Satellite transponder redundancy requirements drives significant test time

Component	Quantity
Receivers	4
Traveling Wave Tube Amplifier	30
Electronic Power Conversion Units	30
Channel Amplifiers	30
Switches	60+
Input Multiplexers	2-4
Output Multiplexers	2-4
Diplexers	2
Temperature sensors	100+
Command/Telemetry Interface Units	2
Cross-strapping	24 for 30

backplane. Many satellites incorporate a MIL-STD-1553 data bus architecture which can be accessed by bus controllers and monitors. This structure has the added advantage that telemetry can be sampled at higher data rates than via the satellite sampling and decommutation scheme. In this way, automated test tools and integrated architectures can tie the bus test interfaces (e.g. power, simulators, analyzers, etc.) and satellite responses into an integrated and automated test infrastructure as scoped in Figure 13. A clear result of this integration is more comprehensive testing of all satellite telemetry points at far faster time durations than possible with operator intervention and control. This integrated and automated test infrastructure will provide the largest area of improvement toward the objective for a one-third reduction in test time.

Figure 13: Potential improved satellite test interface



CONCLUSION

There clearly are significant applications for automation technology in the evolution of satellite testing. If applied thoughtfully along with the "test as you fly" approach, such as proposed in this paper, satellite testing can deliver more comprehensive testing with cost and schedule reductions across the industry. However, to bring about this evolution, a partnership will need to be established among the government, the satellite manufacturers, and the test equipment industry to implement the right technologies and ideas to the right applications based on each group's inherent contributions. From the U.S. government, the call for more comprehensive testing and trending is needed. From the satellite manufacturers, the designs of the satellites need to be applied against the current automation tools. Finally, from the test equipment industry, the existing capabilities and valuable automation knowledge gleaned from serving the needs of terrestrial industries must be employed to generate a significant contribution to the overall evaluation of the satellite test life cycle.

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