A Virtual Ground Station for Automated Spacecraft Health Monitoring

1st Varsha Parthasarathy
Department of Mechanical Engineering
University of Manitoba
Winnipeg, Canada
parthasv@myumanitoba.ca

2nd Philip Ferguson
NSERC/Magellan Aerospace
Industrial Research Chair in Satellite Engineering
Department of Mechanical Engineering
University of Manitoba
Winnipeg, Canada
philip.ferguson@umanitoba.ca

Abstract

Low-earth orbit satellite constellations enable important services on very large areas in a uniform way. Traditional spacecraft communication typically requires manually-staffed ground stations with space systems experts controlling and monitoring bus and payload systems on each pass. With the move from single spacecraft to constellations of many small spacecraft, this model of spacecraft management quickly becomes infeasible from a time and cost perspective. This paper describes the potential advantages of an automated virtual ground station model using Statistical Process Control (SPC) to streamline spacecraft operations and minimize the demand on highly-skilled spacecraft systems engineers. The virtual ground station would minimize the number of personnel involved in daily operations. With the virtual ground station managing the passes and predicting behaviour between passes, controllers will be able to virtually interact with the spacecraft at any time (even between ground station passes). The SPC module functions as a fault-management system decreasing the operations time and manpower by more than 50%. This system is applicable to small and large scale missions, providing an opportunity for mission cost savings. This paper examines how this virtual spacecraft ground station could improve overall ground station operations by identifying potential problems early and notifying engineers only when required.

I. Introduction

The space industry has come a long way since the launch of the first satellite. There have been tremendous advancements in satellite communications and automation, but challenges still exist [1]. Traditional satellite operations require expert teams of highly-trained engineers, scientists and technicians to monitor and command a spacecraft during every ground pass. This level of human / spacecraft interaction is demanding, costly, time-consuming and error-prone [2]. In today's age, constellations of spacecraft such as Canada's RADARSat Constellation Mission (RCM) [3] are becoming more common since groups of satellites provide better reliability, lower cost and better science data return through repeated ground passes. This amplifies ground operations challenge, since each spacecraft will have its own idiosyncrasies that must be managed individually, often on limited budgets (usually the case for small satellite missions). Automating this process would lead to greater efficiency, leaving the expert teams able to focus their attention on more complex challenges as opposed to mundane spacecraft maintenance. As an example, a Low Earth Orbit (LEO) constellation to provide global services (*e.g.*, remote sensing or communications data) requires approximately 40 to 80 spacecraft to provide global coverage [4]. With each spacecraft making multiple ground station passes daily, staffing the station for these passes, managing the data, and monitoring for anomalies would be infeasible without a large, dedicated team. An automated ground station system would streamline the ground station operations processes and reduce the burden on financial and human resources. In addition, monitoring spacecraft at regular intervals traditionally demands constant human attention. Satellite visibility from Earth can be limited, which requires fast satellite to satellite handover especially for communication satellites. This puts tremendous strain on the experts or engineers and operators, potentially leading to costly mistakes and significantly influences the costs of mission operations. These activities currently represent a significant portion of the total mission cost (*i.e.*, 20% to 30% [5]). An automated ground station would be capable of performing normal housekeeping activities, thereby, reducing the dependency on subsystem experts and mitigating the risk of human error. This paper describes a semi-autonomous ground station (also referred to as virtual ground station) and human/satellite user interface architecture, utilizing technologies from Statistical Process Control (SPC). This system automates human/spacecraft interactions by assisting in monitoring spacecraft telemetry and flagging situations that could indicate impending failures. The system is tested using a modified form of the Turing test. This helps assess the validity of the system and the probability of its applicability by ground operators.

II. Advantages of the virtual ground station

Historically, managing and controlling spacecraft from the ground has been a very manual activity. A "virtual ground station" facilitates interaction between the satellite, operations and science teams. A continually-updated spacecraft model powers a user-facing ground station terminal. This allows operators to interact with the virtual ground station by sending and receiving data as if the spacecraft were in continuous view of the ground station at all times, since the operators always interact with the spacecraft model, as opposed to the spacecraft itself. The virtual ground station manages every real pass, when available, to upload stored commands, download telemetry since the last pass and update / maintain the ground station model of the spacecraft. The SPC part of the system monitors telemetry from the spacecraft to perform early fault diagnosis. This provides the ground station with the capability to take autonomous corrective action in some cases and triggers an alert to a human operator for more serious abnormalities. Additionally, the control limits as part of SPC in the system define "normal" telemetry ranges, behaviours and measurements from the spacecraft systems, including the guidance, navigation, control, power, thermal, communications and computing systems onboard the spacecraft. These reduce the need for highly-trained engineers to attend and analyse every ground station pass from every spacecraft in a constellation to ensure safe and efficient spacecraft operation. Engineers can focus on more complex and intricate problems that need their attention.

This system will allow aerospace companies and amateur satellite operators to leverage the power of modern statistical process control techniques while operating constellations of spacecraft. This will streamline spacecraft operations teams by eliminating the trivial housekeeping activities typically required for traditional ground interactions.

III. Past research

A. Autonomous ground stations

There has been considerable research done on autonomous and virtual ground stations for satellite communication in the past. *R Holdaway* [5] developed a program for autonomous ground station controls of small satellites. This system includes features such as automatic and eventual autonomous checking of critical data during real-time passes to identify abnormal parameters, automatic reception and storage of downlink telemetry, open-loop tracking of high altitude satellites, prediction of tracking data for a week, and automatic dialing to expert engineers when in need [5]. It utilizes a closed-loop feedback of error-signals into the orbit determination to autonomously update the predicted orbit parameters for the future [5]. *Anderson* [2] has a different approach to automating satellite operations for CubeSats specifically. The operations are analysed for their automation potential using attributes such as their ability to be inspected, predicted or repaired within the existing ground systems architecture. A "score" based on these (and other) attributes helps identify which operations should be automated. Several existing systems including GENIE (Generic Inferential Executor) are analysed and ranked according to the scoring system. It was observed that GENIE (Generic Inferential Executor) reduces the required labour by 50% in the case of a typical NASA command centre where two people, namely the command controller and spacecraft analyst, would be staffed per satellite per shift [2]. The command controller decides which commands to send based on input from the analyst who monitors the spacecraft's health and is technically the 'expert'. While useful, GENIE has no statistical monitoring capability (for detecting subtle changes that could suggest an early stage fault) and is often too slow to be executed in real-time [2].

B. Statistical process control

SPC plays a critical role in the virtual ground station system. SPC is a traditional, charting, monitoring and diagnostic tool that the manufacturing industry has been using for decades to improve and maintain product quality [6]. SPC works on the theory that a process behaves predictably to produce products which conform to engineering requirements causing the least possible waste (*i.e.*, scrapped product). When a process is not behaving properly, key metrics can be identified that can indicate early signs of trouble. SPC has been used in industrial applications since the 1920s when chart patterns were analysed and interpreted manually [7]. In the 1980s, with technological advancement and changing needs of the manufacturing industry, manual methods for creating and analysing control charts were no longer sufficient. This led to the idea of expert systems and other computing technologies. This was explored by researchers like *Swift*(1987) [8] and *Cheng* (1989) [9]. *Cheng* focused his research on the application of SPC in small-batch manufacturing using expert systems concepts [9]. In the 1990s, with the development of artificial neural networks for SPC chart pattern recognition, researchers overcame drawbacks in the previous expert system approaches by improving the handling of non-linear data, fault tolerance and adaptability. *Sohn et al.* [10] performed vibration-based damage diagnosis using SPC. This is done using data compression for feature vector extraction through control chart analysis which is very suitable for automated continuous system monitoring. This is applied to specific features to identify damage in structures. New data is compared to past data sets and this information is used by X-bar SPC charts to monitor abnormal changes.

SPC tools developed for the system described in this paper are beneficial in many ways. It will make it possible to monitor a constellation of satellites with ease. Key telemetry items (such as bus voltage, current, pointing angle or solar insolation angle) are analyzed through automated control charts to detect issues that require attention. Patterns, trends and out of control conditions aid in continually verifying if the "process" (*i.e.*, spacecraft operations) is in equilibrium. It also acts as a visualization tool to facilitate the assessment of various subsystems' performance. Most importantly, the use of SPC will reduce the dependence of satellite monitoring on human resources to a large extent, which is especially important when considering the growing popularity of constellations of satellites.

Though SPC has been part of the space industry in the form of manufacturing quality control, it has not been used in satellite operations and maintenance. This research employs SPC for spacecraft health monitoring. This will reduce the dependence of satellite monitoring on human resources to a large extent especially considering the growing popularity of constellations of satellites. It is the first system to use SPC combined with a detailed spacecraft mathematical model to streamline satellite operations.

C. Turing test

A modified version of the Turing test is used in the testing of the virtual satellite model. In 1950, the Turing test (TT) was proposed by *Alan Turing* [11] to broadly answer the question "Can machines think?" [12]. In general, interpretations of TT's goals in machine intelligence as trying to assess the machine's ability to imitate human being. This assessment takes place in the form of a game which is played between a machine (A), a human (B) and an interrogator (C). The aim of C is to determine which one of the two participants he/she is communicating with is the human. If C is able to identify the human correctly, it implies that the machine hasn't been able to imitate a human well-enough and hence, the machine has failed the TT [12]. *Turing* [11] opined that in order to imitate an adult human mind, we should consider the initial state of the mind, the education it has been subject to and the experiences the mind has been through. These should be used to make the machine learn using techniques as closely related as possible to the learning methods used by humans [11] [12]. A modified form of Turing test is used in the testing of the virtual satellite model, since the virtual ground station is attempting to imitate the actual satellite. The success of the virtual ground station will, in part, be evaluated on how well it can fool the human operator into thinking they are communicating with the actual spacecraft.

Moor [13] hypothesizes that the test provides a sufficient condition for intelligence-granting and learning for machines. Though all researchers might not agree, and it might not be a sufficient condition, it could be considered a necessary condition for testing the learning component in artificial intelligence. *Horn* [14] has done substantial research in validation of simulation models. He suggests that a set of statistically significant conclusions can be drawn from any simulation. The testing and behaviour of a system process is dependent on interaction between the system's components. To increase the confidence in a simulation, psychological and field tests were conducted. Similar tests as part of the modified Turing test for the virtual ground station helps assess our confidence in the system and how likely are ground operators to use it. The probability of passing the Turing test increases as the similarity in behaviours of the virtual system and actual spacecraft increases. The main difference between the modified Turing test to a traditional Turing test is the involvement of two machines, *i.e.* virtual spacecraft model and the actual spacecraft.

IV. Conceptual description of the virtual ground station

The conceptual model of the virtual ground station is given in Figure 1.

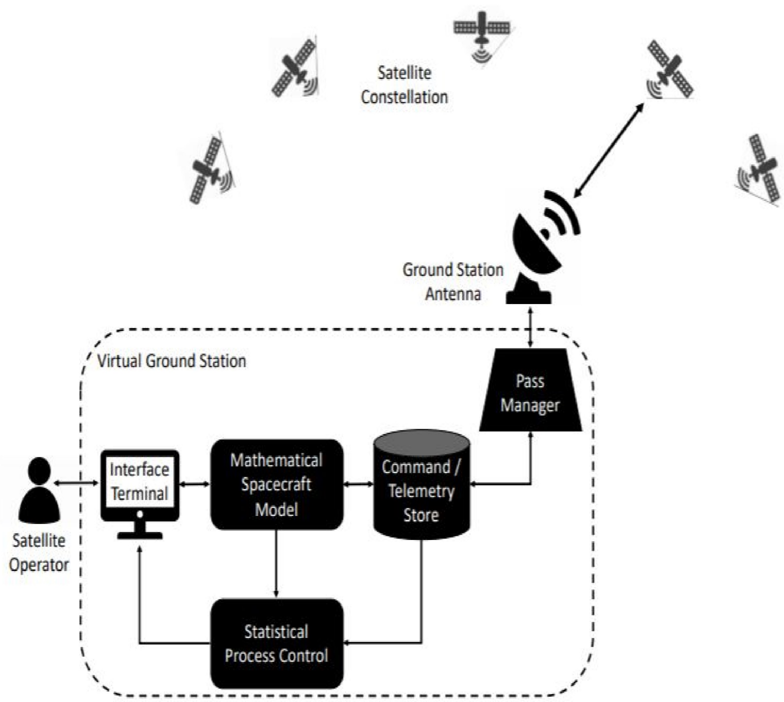

Fig. 1. Conceptual Model of the Virtual Ground Station

The virtual ground station is made up of two primary components. The first component comprises a mathematical model of the spacecraft systems, along with a communications "pass" manager that handles actual command and data transmissions with the spacecraft. The user interface terminal accesses data from the spacecraft model, providing the user with either real data from the past or predicted data for "live" data requests for which real data has not yet been linked to the ground. The second component of the virtual ground station is a Statistical Process Control module that monitors the real telemetry streams from the spacecraft and compares them with the model and historical data to identify potentially anomalous operations.

A. *Main functions:*

a) Virtual Satellite Model: The virtual ground station developed based on a mathematical model of the spacecraft is responsible for abstracting away spacecraft communications logistics, giving ground operators the sense of a spacecraft in continual communication at all times.

b) Statistical Process Control: Traditional analysis techniques from the field of automated Statistical Process Control provide near real-time health and diagnostic evaluations based on spacecraft telemetry trends and how they change over time.

B. *Component description, methodology and testing*

This section describes the development, methodology and testing of the main components of the virtual ground station:

1) Virtual satellite model: The virtual satellite model simulates constant spacecraft communication, regardless of the spacecraft's position with respect to the ground stations. A simulated spacecraft model continually predicts the system output, based on the commands uploaded by the operator. When the spacecraft passes over the ground station, the pass manager establishes communications, uploads commands that have been issued since the last ground station pass and downloads the latest spacecraft telemetry. Between passes, the ground terminal provides data from the virtual satellite model immediately upon request. In this sense, users/operators can obtain expected spacecraft responses to commands without having to time their requests with physical ground station passes. Once the virtual ground station receives real data, the historical record of spacecraft operations are automatically updated with the real data. This simulated model of the actual spacecraft gives us an idea of what the telemetry received from the satellite in orbit should look like by providing predicted values of various parameters considered in this research which are:

- Current into / out of battery
- Main solar panel current
- Computed angle our payload is pointing with respect to the sun
- Reaction Wheel torques
- Reaction Wheel currents
- Bus voltage
- Earth's magnetic field measurements (from the magnetometer)

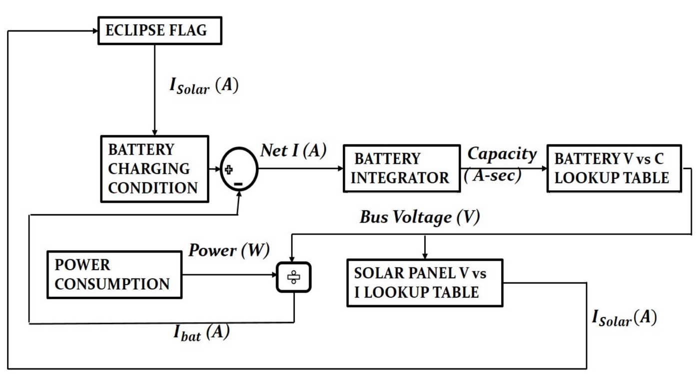

Fig. 2. System block diagram for the power subsystem simulator

As an example, the functional diagram of the power subsystem simulator is provided in Figure 2.

a) Methodology: The model is developed in the Matlab/Simulink environment. Rigid-body simulations, a simple orbit propagator and electrical power subsystem simulator are developed. This model receives telemetry from the actual spacecraft through the pass manager. The pass manager essentially knows when the passes would occur and when the telemetry can be expected and sent to other components. The human operators are also be able to extract any data they require from the virtual model. As an example, the functional diagram of the power subsystem simulator is provided in Figure 2.

The pass manager and command/telemetry logs are incorporated and provide seamless interface to operators even when the spacecraft is not in communications with the ground station. To verify performance of the pass manager, two spacecraft simulations are maintained: the "real" spacecraft and the "virtual" spacecraft. Once all the subsystem models and simulations for one spacecraft are done, the simulation will be expanded to include an entire fleet of spacecraft. A ground station front end is created that enables the user to send commands and receive data.

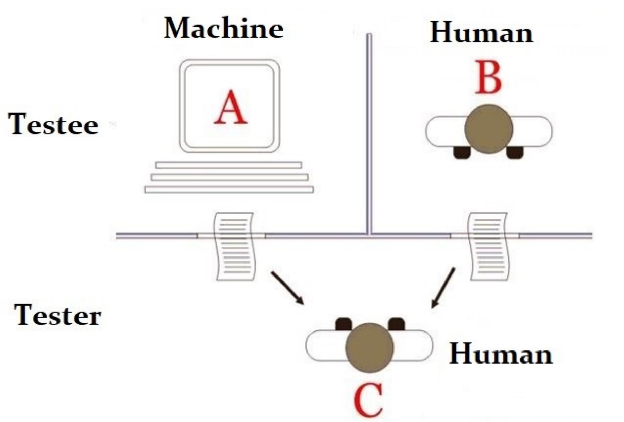

Fig. 3. Turing test [12]

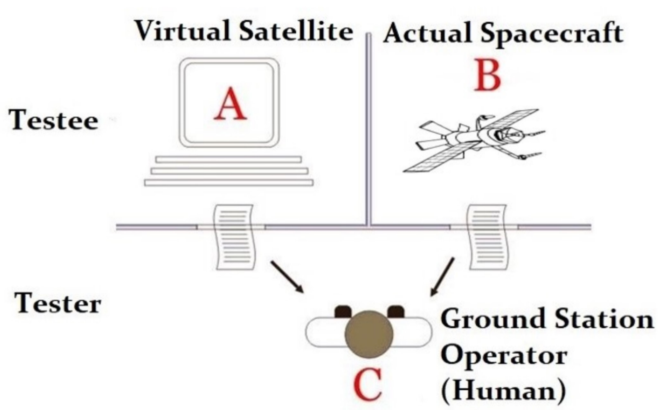

Fig. 4. Modified Turing test [12]

b) Testing: The virtual model should be able to function the same way as the actual satellite, such that the human operator cannot tell the difference between the virtual satellite and the actual satellite. This is done using a modified version of the Turing test. The Turing test (see Figure 3) is the de facto test to assess the ability of a computer to think, requiring participant to be unable to detect the covert substitution of the human by a machine. In this case, we want the human operators to find no difference between when they interact with the virtual spacecraft model and the actual spacecraft. The traditional Turing test involves two human participants (interrogator and human) and one computer [12]. In our case, the interaction is between a human operator, the real spacecraft and the virtual spacecraft. Hence, we use a modified version of the Turing test (see Figure 4) which enables us to evaluate the virtual spacecraft's ability to "fool" the operator into thinking it is the real spacecraft they are communicating with.

2) SPC module: The purpose of the SPC module is to automatically monitor spacecraft telemetry streams for early signs of spacecraft anomalies. While some critical spacecraft failures are obvious, such as a tumbling spacecraft, loss of power or complete unresponsiveness, many failures are subtler and could indicate precursors to a catastrophic event. For example, the electronics on a reaction wheel may slowly begin to require more current due to a bearing starting to show premature wear (potentially due to a manufacturing error). Initially, this issue would present itself as merely slightly more current than normal, but still well within the acceptable bounds provided by the reaction wheel manufacturer. If left unchecked, this issue could lead to the reaction wheel drawing down the entire power bus as the motor draws more and more current. Even worse, the bearing could suffer a dramatic failure, resulting in the sudden cessation of the wheel and either a tumbling spacecraft and/or a damaged structure. If ground operators could be made aware of the degradation before it escalates into a failure, they could switch to a redundant unit or modify operations to avoid the failure.

As described above, industrial SPC provides the tools to identify processes that are going "out of control", such as the previous example with the reaction wheel. The SPC module uses industry-standard SPC algorithms to monitor various spacecraft bus systems for anomalous behaviour as evidenced by abnormal patterns in the data. Publicly-provided spacecraft housekeeping data is used to establish baselines for "normal" telemetry. This data is initially taken from the ManitobaSat-1 [15] CubeSat (currently in design at the University of Manitoba), but will expand to include data from other Canadian CubeSat Program spacecraft as test data becomes available.

a) Methodology: The SPC module uses the expected outputs from the virtual satellite model to detect out of control conditions and provide notifications/diagnostics to users when appropriate. As SPC detects abnormalities by identifying patterns in the test data, custom signal patterns are generated using equations provided in [16] to establish appropriate SPC responses. A challenging aspect of designing the SPC module is that similar statistical properties may be derived for some patterns of different classes, which may lead to incorrect recognition. This can be overcome by appropriate thresholds using multiple sets of raw and simulated data. Matlab is used to establish prototype SPC monitoring agents, starting with simple models and injected anomalies. For example, for the power subsystem, anomalies include the sudden increase in battery resistance and failure of few solar cells during the mission. In SPC, process behaviour charts called control charts are used to determine if a process is in equilibrium or in statistical control [17]. A typical control chart as seen in Figure 5 has a centre line, upper and lower control limit lines [19]. These are used along with SPC control rules (see Table I) to detect anomalies.

In Table I, zones A, B and C refer to regions between a control limit and 2sd, 2sd and 1sd and 1sd and the mean respectively where sd is the standard deviation of test data set. The control rules and charts enable identification of upward and downward trends, mixtures with no points in certain zones, stratification and over-control to indicate that the process is not in equilibrium. Each of these conditions or patterns typically points to a specific type of defect, which are identified by studying real and simulated data. The developed algorithm is verified with the simulated data as well as the actual data set to determine if it provides reasonable classification results. Data points crossing pre-defined control limits trigger alarms with varying severity, depending on the excursion.

b) Testing: Once the SPC module is developed, the testing phase starts. In the case of all the simulators, noise and known failures are injected to the model to verify the SPC module's ability to correctly identify anomalies. The same testing is done with real satellite data with failures injected.

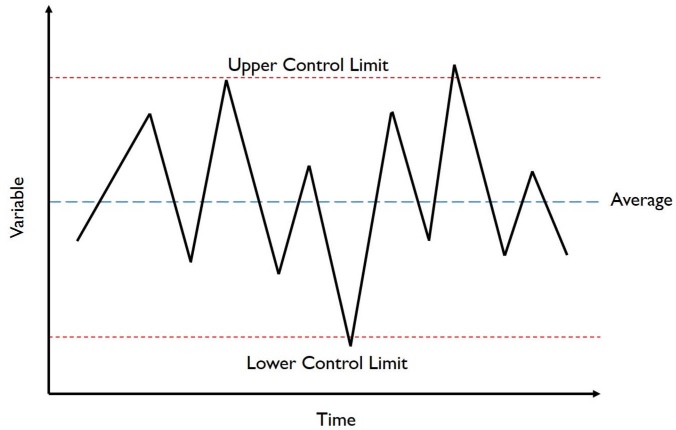

Fig. 5. A typical control chart

TABLE I
SPC CONTROL RULES [18]

Rule number	Rule description
1	One or more points beyond the control limits
2	Seven or more points in a row on the same side of the mean
3	Seven points or more points in a row continually increasing or decreasing
4	Fourteen or more points in a row alternating up and down
5	Two out of three points in a row are more than 2 standard deviations from the mean in the same direction (zone A or beyond)
6	Four out of five points in a row are more than 1 standard deviation from the mean in the same direction (zone B or beyond)
7	Fifteen points in a row are all within 1 standard deviation of the mean on either side of the mean (zone C)
8	Eight points in a row exist, but none within 1 standard deviation of the mean, and the points are in both directions from the mean (no points in zone C)

This is done step by step for every subsystem in each stage of testing starting with the simulated power subsystem, followed by the attitude control, orbit control, thermal control and communications subsystems.

V. Concluding remarks

The virtual ground station system described will advance management and control of spacecraft from the ground by empowering spacecraft ground controllers and reducing operation costs significantly. This is especially useful when dealing with a constellation of satellites. Highly-trained and qualified engineers would no longer be required to initiate communication with the spacecrafts, get downlink data and send routine commands. The implemented statistical process control techniques provide the capability to detect impending failures and subtle anomalies which may not be identified by even seasoned experts. That being said, there are several features that can still be researched to enhance the efficiency of the system. The SPC module can be extended to include sophisticated and more advanced waveform analyses. Learning capabilities could enhance the efficiency of the system.

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