# Telemetry Anomaly Detection System using Machine Learning to Streamline Mission Operations

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Abstract— Spacecraft housekeeping telemetry is monitored at flight control centers by the operations engineers using tools that can perform limit checking or simple trend analysis. Recent developments in machine learning techniques for anomaly detection enable the implementation of more sophisticated systems that aim to augment current state-of-the-art mission tools to provide valuable decision support for the spacecraft operators, assisting in anomaly detection and potentially saving console time for the engineers. We will show results of the implementation of an anomaly detection tool for the NASA Mars Science Laboratory mission.

## Keywords—anomaly detection, machine learning

## I. INTRODUCTION

Evaluating the health state of current flight and ground systems using traditional parameter limit checking, modelbased, or rule-based methods is becoming more difficult as system complexity grows. Data-driven monitoring techniques are complementary to the current methods and have been developed to analyze system operations data to automatically characterize normal system behavior. System health can be monitored by comparing real time operating data with these nominal characterizations, providing detection of anomalous data signatures indicative of system faults, failures, or precursors of significant failures. While rule-based methods can only flag known anomalies, data-driven methods go a step further in generalizing to a wider range of anomalies beyond those specifically detected in historical data.

The deployment of machine learning tools to the mission operations environment may assist spacecraft operators by detecting anomalies (known or never seen before) in the telemetry received from the spacecraft. We provide a proof of concept applying these methods to MSL mission data. We initially developed a prototype and then an operational tool that can be used by the MSL flight operations team. Yisong Yue and Romann Weber Computing and Mathematical Sciences California Institute of Technology Pasadena, United States yyue@caltech.edu, romann.weber@gmail.com

## II. MARS SCIENCE LABORATORY USE CASE

Part of NASA's Mars Science Laboratory mission (MSL), Curiosity [1] is the largest and most capable rover ever sent to Mars. It launched November 26, 2011 and landed on Mars at 10:32 p.m. PDT on Aug. 5, 2012 (1:32 a.m. EDT on Aug. 6, 2012).

The mission team at NASA's Jet Propulsion Laboratory in Pasadena, California exalted at radio confirmation and first images from Curiosity after the rover's touchdown using a new "sky crane" landing method. Transmissions at the speed of light took nearly 14 minutes to travel from Mars to Earth, which that day were about 154 million miles (248 million kilometers) apart. Curiosity (Fig. 1), accomplished its main goal in less than a year, before reaching its main science target, Mount Sharp. It determined that an ancient lake environment offered the conditions needed for life -- fresh water, other key chemical ingredients and an energy source. With higher destinations ahead, Curiosity will continue exploring how this habitable world changed through time.



Fig. 1. Curiosity rover self-portrait on the surface of Mars (image credit NASA JPL).

As Curiosity celebrates its 5-year anniversary this year, it keeps gathering great amounts of data that can be studied and analyzed to assist in the anomaly detection effort. It is critical to keep Curiosity running flawlessly to maximize science return. Fig. 2 shows the rover's route since landing:



Fig. 2. Curiosity rover path over the past five years (image credit NASA JPL).

The current methods to monitor telemetry are mainly based on parameter limit checking, where a reference table of nominal telemetry channels is compared against real-time telemetry to determine if the values fall within the ranges. If not, then that channel may have an anomaly. This method of health monitoring is very inefficient and time consuming because as the number of components increase, the generation of this reference table becomes extremely hard. It is difficult to correctly determine what would constitute a healthy channel value. Multiple reference tables would have to be made for each of the spacecraft operational modes due to different component interactions. Another drawback of such an approach is that it only considers individual parameter ranges when making its decision, and cannot model complex interactions that may involve several concurrent parameters in the operating context [2].

We propose to complement the current systems by developing an anomaly detector based on known machine learning techniques. Such an approach can have many benefits. Models trained on historical data can learn to recognize both nominal and off-nominal behaviors, including never-before-seen anomalies reaching the goal of reducing the time required to evaluate system health and identify and resolve the root cause of anomalies. This anomaly detector could be part of a [6] fault management (FM) system designed to provide offnominal state detection and isolation capabilities that are key components to assessing spacecraft state awareness. Efficient real-time diagnosis allows problems to be solved quickly, especially in time-critical situations where delays in evaluation increase the risk of losing the spacecraft. Accelerating anomaly identification saves operator time and avoids the need to process specific data channels unless the system flags data anomalies. This system is the first step towards reducing operator console time.

Fig. 3 shows an example of the different types of data that the operations engineer needs to evaluate:



Fig. 3. Anomaly detection by the spacecraft operator- systems involved.

### **III. TELEMETRY ANOMALY DETECTOR SYSTEM**

We have studied historical data and past anomalies and it is not uncommon that a whole week of planning could be severely disrupted due to anomaly investigations, which impacted science activities, and ultimately science data return. A tool that could provide early warning of the anomalies would benefit MSL and future Mars missions such as Mars 2020.

We started the process by architecting a prototype set of building blocks shown in Fig. 4:



Fig. 4. Prototype set of building blocks.

Channel data, Event Record (EVR) and data products could be analyzed and run through the anomaly detection system to generate a daily high-criticality anomaly report and eventually update the system to be able to generate a predicted future anomaly report.

The work covered in this paper describes the first phase of the project that includes performing anomaly detection of individual telemetry channels (only channel data) providing the operator with the current high-criticality anomaly report. Future work includes augmenting the system to also provide a predicted anomaly report.

We queried data from the NASA Advanced Multi-Mission Operations System (AMMOS) Mission Data Processing and Control System (AMPCS). The high level architecture diagram is shown in Fig. 5:



Fig. 5. High Level Architecture Diagram for the MSL anomaly tool.

The first step was to use the prototype to ingest only channel data. We had to become familiar with the MSL telemetry in order to perform data exploration and preparation to develop an anomaly detector that would meet the requirements needed by the MSL project. The first subsystem we analyzed was telecommunications, which provides communications functions to the spacecraft for uplink (Earth to spacecraft link for commands and load data) and downlink (spacecraft to Earth for science and/or engineering telemetry data).

There are two separate subsystems:

- 1. X-Band for direct to/from earth (DTE/DFE)
- 2. UHF subsystem for data relay to/from Mars orbiting assets

The surface telecom system uses three antennas: two for Xband DTE/DFE and a UHF antenna for relay to an orbiting asset [1].

The X-band antennas are the Rover low-gain antenna (RLGA) and the high-gain antenna (HGA). The HGA is used for either DTE commanding or DFE telemetry, while the RLGA is used primarily for low-rate (contingency) DFE commanding. The downlink signal level achievable using the RLGA is too low for all but special DTE applications.

The anomaly detector ingests the housekeeping telecom telemetry from MSL that covers X-Band, UHF-Band and Monitor Deep Space Network (DSN) channels. Data are queried and read in raw format. For each Martian sol, the channels under study are analyzed to detect anomalies. Each channel represents a time series that includes the channel value in Engineering Units (EU) or Data Number (DN), and the time associated with the channel value.

Finding the periodic patterns contained in time series data, requires some analyses. A time series *Xt* usually has three components:

- 1. Trend component *Tt*
- 2. Seasonal component St
- 3. Residual component et

A method to perform a seasonal decomposition of Xt is by determining Tt using a Loess regression (linear regression plus k-nearest-neighbors), and then calculating the seasonal component St and residuals et, from the differences Xt - Tt [3]. The residual component of the time series is extracted from the input time series and then statistical learning techniques [4, 5] are applied to automatically detect anomalies in MSL telemetry data.

We developed an operational tool named **MARTTE**: **MSL** Anomaly Detecto**R** Telemetry Tool SuitE that is capable of ingesting the MSL telemetry files as inputs and displays to mission operations staff a list of high interest anomalous telemetry readings. The tool suite delivered to MSL OPS includes a command line tool and a web interface tool. We also have a third tool also part of MARTTE that is still in a research state that will not be described in this paper. MARTTE ingests the MSL telemetry (time series data) and is capable of generating the following ouputs for the operations engineer:

-A histogram mapping Engineering Units (EU) to frequency over the specified sol (598) for a specified channel (TEL-5211)

-A histogram mapping EU to frequency over the specified sol (598) AND over the course of all previous sols (over the past 100 sols) for channel (TEL-5211)

-Summary statistics (mean, median, standard deviation) for channel (TEL-5211) for specified sols (498-598)

-A plot of time vs. EU, with a blue circle highlighting the points the algorithm found to be anomalous.

-A black and white point plot of time vs. unit (EU)

-A table listing all of the timestamps and channel values that the algorithm predicted to be anomalous

# A. Command Line Tool

We will walk through an example of how the command line tool works to generate image files (histogram of many sols, expected anomalies) and to generate a CSV with the expected anomalies. First, we run the script to find anomalies regarding a specific sol number on the selected channels of interest. We will have our anomaly detection system look at the telemetry data pertaining to that specific channel over the last 99 sols to give it a better, more reliable sense of normal behavior. For this run, we will look at EU data, but there is the option to use DN (Data Number).

-rw-r--r-- 1 mmmsltel msltel 36563 Dec 20 19:07 histogram\_many\_sols-501\_to\_600\_TEL-5211\_eu.png -rw-r--r-- 1 mmmsltel msltel 140336 Dec 20 19:08 anomalies-identified-501\_to\_600\_TEL-5211\_eu.png -rw-r--r-- 1 mmmsltel msltel 2240 Dec 20 19:08 anoms\_table-501\_to\_600-TEL-5211\_0.001\_0.05.csv

MARTTE generates the histogram and anomalies tables as shown in Fig. 6 and Fig. 7:



Fig. 6. Histogram generated with MARTTE



Fig. 7. Telemetry anomalies flagged by MARTTE

If the user wants to generate plots and csv files for multiple channels, it is also possible:

-rw-r--r-- 1 rmmsitel msitel 36563 Dec 20 19:44 histogram\_mony\_sols-501\_to\_600\_TEL-5211\_eu.png -rw-r--r-- 1 rmmsitel msitel 140336 Dec 20 19:45 anomalies-identified-501\_to\_600\_TEL-5211\_eu.png -rw-r--r-- 1 rmmsitel msitel 2240 Dec 20 19:45 anoms\_table-501\_to\_600\_TEL-5211\_0.001\_0.05.csv -rw-r--r-- 1 rmmsitel msitel 49331 Dec 20 19:46 histogram\_mony\_sols-501\_to\_600\_TEL-5210\_eu.png -rw-r--r-- 1 rmmsitel msitel 135623 Dec 20 19:47 anomalies-identified-501\_to\_600\_TEL-5210\_eu.png -rw-r--r-- 1 rmmsitel msitel 1566 Dec 20 19:47 anomalies-identified-501\_to\_600\_TEL-5210\_eu.png

# B. Web Interface Tool

The web interface tool provides the same functionality as the command line tool. The reason we also developed the command line tool was to be easily integrated with the rest of the MSL team tools.

When running the tool, we obtain the following GUI to interact with the user in order to provide the required inputs such as a the channel of interest, sol to analyze or data units as it is shown in Fig. 8. We will show and example of how MARTTE detected the sols 596 and 598 uplink anomalies. The flagged anomalies by the tool are shown in Fig. 9. They correspond with real anomalies reported by the MSL team. The tool generates a histogram and provides a list of the anomalies detected as shown in Fig. 11.

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Fig. 8. MARTTE web interface tool display



Fig. 9. Data sample of MSL telemetry to be analyzed where two anomalies were detected.

The MSL mission has a remarkably reliable channel for sending command products to the rover. However, problems can arise that result in loss of activity during uplink. Noise encountered on the millions of kilometers trip can corrupt the signal beyond the means of error correction codes to correct. Hardware failures on Earth ground stations can occur with insufficient time to repair before the uplink window. Fig. 10 (SNR vs time) illustrates the details of 598 uplink anomaly where the commands were not uplinked to the rover. We notice the signal toggling lock on the left part of the plot that already shows signs of anomalous behavior. All of these anomalous telemetry values were successfully detected by MARTTE.



Fig. 10. Detailed view of uplink anomaly on Sol 598.



timestamp	anoms
2014-04-12 10:20:24	18.22
2014-04-12 10:20:54	18.22
2014-04-12 10:21:24	18.22
2014-04-12 10:21:54	18.22
2014-04-12 10:22:24	18.22
2014-04-12 10:22:54	18.22
2014-04-12 10:23:24	18.72
2014-04-12 10:23:54	18.22
2014-04-12 10:24:24	18.22
2014-04-13 10:53:58	18.22

Fig. 11. Anomalies flagged for a specific run of MARTTE

We worked very closely with the MSL ground data systems team to make our tools operational in the red ops venue. It was the first time they tested this type of tools so there was some learning involved at the beginning to make sure that we were covering all cases to make MARTTE fully operational. Tools have been run in real time during the telecom shifts and they operate nominally. It only takes about 10-20 minutes to run it helping save time for the telecom operator. It warns of any possible unexpected value. The operator could work remotely monitoring the tool output. It used to take approximately. After each downlink, it used to take the telecom operator almost 4 hours to analyze all the data and evaluate system health. With the new automated system where MARTTE is integrated in, each sol can be analyzed in barely an hour. The MARTTE tool was tested in real ops for MSL and was run through historical data to see if it was able to detect known anomalies. Preliminary results indicate that for the initial channels tested, where we optimized the learning parameter of the algorithm (for that specific channel), MARTTE scores a false alarm rate of only 4%. MARTTE also detected unexpected system behavior that may have not been noticeable with the traditional tools.

Fig. 12 shows the GUI outputs and terminal outputs highlighting the anomalies detected by MARTTE:

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Fig. 12. MARTTE output including detected anomalies.

## CONCLUSIONS

The MARTTE: MSL Anomaly DetectoR Telemetry Tool SuitE was prototyped, developed, tested and delivered fully operational to the MSL red OPS team with the capability of detecting the unexpected values in the MSL telemetry to reach the goal to assist the operations engineers monitoring the health status of the spacecraft. A major advantage over conventional anomaly detection methods is that this approach requires little *a priori* knowledge of the system.

Future plans would include developing the second step which would provide a predicted future anomaly report. This work showcases the benefits of complementing the traditional systems with new tools incorporating recently developed machine learning techniques developed in recent years to assist operators in early detection of spacecraft anomalies.

## ACKNOWLEDGMENT

The authors would like to acknowledge the MSL project for funding this research and the telecom team that provided telemetry data to analyze and test the system, especially Jim Taylor for his advice and insight. Thanks to Suzanne Stathatos and the MSL GDSIT team for their contributions to this task. The work described in this presentation was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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