

UNIVERSITY OF WASHINGTON

**Techniques for Correlation and
Visualization of Telemetry Dependence
Relationships for Root Cause Fault
Analysis in Complex Systems**

by

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degree of Master of Science in Aeronautics & Astronautics

in the
William E. Boeing Department of Aeronautics & Astronautics
University of Washington College of Engineering

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Declaration of Authorship

I, NATHANIEL GUY, declare that this thesis titled, ‘TECHNIQUES FOR CORRELATION AND VISUALIZATION OF TELEMETRY DEPENDENCE RELATIONSHIPS FOR ROOT CAUSE FAULT ANALYSIS IN COMPLEX SYSTEMS’ and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

Date:

“Okay, 13. We’ve got lots and lots of people working on this; we’ll give you some dope as soon as we have it, and you’ll be the first one to know.”

Jack Lousma, Apollo 13 CapCom [\[8\]](#)

UNIVERSITY OF WASHINGTON

Abstract

William E. Boeing Department of Aeronautics & Astronautics
University of Washington College of Engineering

Master of Science in Aeronautics & Astronautics

by Nathaniel Guy

This thesis explores new ways of looking at telemetry data, from a time-correlative perspective, in order to see patterns within the data that may suggest root causes of system faults. It was thought initially that visualizing an animated Pearson Correlation Coefficient (PCC) matrix for telemetry channels would be sufficient to give new understanding; however, testing showed that the high dimensionality and inability to easily look at change over time in this approach impeded understanding. Principal component analysis (PCA) was used to reduce dimensionality, and the time curve visualization proposed by Bach et al (2015) was adapted to visualize both raw telemetry and telemetry data correlations. Subsequent testing revealed insights into understanding and an intuitive grasp of data families that suggests the viability of this approach to enhance root cause analysis for actual aerospace systems.

Acknowledgements

I would like to thank my advisor, Dr. Mehran Mesbahi, for his academic guidance, his patience, and his constant encouragement as I struggled with the process of determining my own interests in this field. Deep thanks go to Dr. Jeff Heer for his insights and suggestions into the best practices for visualizing the hidden patterns within correlation data. My sincere thanks to Dr. Chris Lum for his opinions and suggestions about aerospace fault detection systems. I'd also like to thank my various internship teams for their guidance and encouragement: the JPL OpsLab team, specifically Scott Davidoff, Jeff Norris, and Garrett Johnson, for introducing me to teleoperation interface design and testing techniques with the Unity 3D game engine; the SpaceX Flight Software team, specifically Mike Soares, Dan Gelband and Derek Bronish, for introducing me to Fault Detection, Isolation and Recovery systems and teaching me much about aerospace ground software systems; and the HAKUTO Lunar XPRIZE team, specifically Dr. Nathan Britton, Louis Burtz, Kurai Shimizu, Toshiro Shimizu, Toshiki Tanaka, Dr. John Walker, and Dr. Kazuya Yoshida for letting me use their lunar rover as a testbed for new ground software design methodologies and fault diagnosis techniques. Special thanks go to Daisuke Kikuchi for countless bits of design advice and for helping to increase the aesthetic appeal of the HAKUTO rover ground station UI. My thanks to the team at Unity, for developing an excellent and adaptive game engine. Finally, I'd like to thank Steve Rabin at Nintendo of America for his advice about fault detection and valuable comparisons to runtime analysis and profiling of executable code. Without the aforementioned people and many others, I would be lost!

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Abbreviations

FD	F ault D etection
FDIR	F ault D etection, I solation, and R ecovery
GSN	G round S tation
PCC	P earson C orrelation C oefficient

Physical Constants

$$\text{Speed of Light } c = 2.997\,924\,58 \times 10^8 \text{ ms}^{-\text{s}} \text{ (exact)}$$

Symbols

σ_X standard deviation of vector X

For Carl, who showed me the way to space.

Chapter 1

Introduction

Complex, remote-operated systems present many problems to engineers and designers who are conscious of mission safety. Complex systems often have detailed and comprehensive rules for the detection of anomalous conditions, or “faults,” but even the most complex cannot capture the full range of possible anomalies that can occur on a system, especially if false positives are a concern and if the user has not thought of all possible conditions. Visualization of fault conditions can be an even greater problem, owing to issues such as the impracticality of simultaneously displaying data from thousands of telemetry channels, organizing data in a logical and discoverable way, maintaining system reliability in the presence of performance constraints, and leaving screen space for other non-fault-related visualization components and control affordances.

Because of these difficulties, root cause analysis can be a very long and difficult task. There are several historical cases of major system anomalies that have required very long periods of concentrated, manual telemetry data analysis (and, in some of the most catastrophic cases, post-disassembly hardware analysis) in order to piece together the root cause for anomalies. Some examples include:

- On October 28th, 2014, the Orbital Sciences “Antares” rocket suffered a catastrophic failure 6 seconds after launch, experiencing a large explosion which destroyed its cargo, which had been bound for the International Space Station. Orbital Sciences immediately launched an investigation to determine the cause, but preliminary root cause data loosely linking the mishap to a failure of one of the AJ26 engines was not publicly indicated until November 5th, and a final root cause assessment has still not, to this date, been released [2]. An independent review team within NASA evaluated telemetry data, historical data and hardware samples, beginning in November 2014, and roughly a year later, issued a report that

was still unable to provide a clear root cause for the mishap, instead linking it to three likely causes, all involving the AJ26 engine which initially exploded [6].

- On July 28th, 2015, SpaceX’s “Falcon 9” rocket, carrying the “CRS-7” payload delivery up to the International Space Station, experienced an overpressure event in the second stage liquid oxygen tank, causing rapid unscheduled disassembly and failure of the mission. SpaceX engineers, working with NASA and the Air Force, began intensively examining system telemetry from the event. Despite SpaceX’s well-known history of transparency about anomalous events and engineering challenges, the root cause of flawed second-stage helium system strut was not publicly identified until nearly a month later, on July 20th [5].
- On December 4rd, 2015, the PROCYON interplanetary cubesat, developed by the University of Tokyo and JAXA, went completely “dark,” ceasing to provide any telemetry data at all. As of February of 2016, attempts to analyze previously received telemetry data in order to gain insight into the cause of the anomaly, and possible ideas for recovery, continue, but no root cause has been able to be determined [4].

As is shown by the cases above, the root cause diagnosis process is very difficult, and can take weeks to months to complete. It involves intense scrutiny of potentially thousands of data channels, and often the only comprehensive understanding of how these data channels relate to each other is encoded in human “tribal knowledge.” Although the examples above are extreme ones, root cause diagnosis can be extremely valuable even with trivial anomalies for gaining a better understanding of system properties and subsystem connections, and the tools to do so that are currently in use are inadequate for the task. Having seen this problem first-hand in the space industry, we set out to examine the space of possible tools that could begin to tackle this problem.

In this thesis, we examine some possible solutions to the long-standing problem of root cause analysis for complex, remotely monitored systems. The paper starts with identification of irregular telemetry via a typical fault detection models, and describes the necessity to characterize anomalous conditions in a more in-depth way than traditional fault detection algorithms allow, in order to identify root causes for anomalies, or to predict the occurrence of anomalous conditions ahead of time. We will point out some of the issues that commonly occur with time series data on multiple channels which can make it difficult to both analyze and visualize.

Next, we will examine traditional methods of analyzing connections between sets of time series data. We will see how solutions to some of the aforementioned issues are

provided by these analytical techniques. We will also examine a number of visualization techniques that have been used in the past to show connections within correlation data.

We will propose a data visualization technique, based on an animated adaptation of statistical correlation matrices. To assess the efficacy of this visualization, we will apply it to simulated data from a sample system, and will show test results when users are given an implementation of this visualization and asked to use it to gain insight into events during a simulated scenario. We will discuss some of the downsides of our techniques that were uncovered by testing.

Next, we will iterate and propose adaptations to address some of the issues in the first round of testing. We will look at analytical improvements as well as new visualizations, borrowing from recent research in the field of temporal data visualization. We will then run another set of human tests on this data to show the effect on user insight.

Finally, we will present our conclusions about the employed analysis and visualization techniques, and will propose avenues for further research.

Chapter 2

Background in Fault Detection, Isolation and Recovery

Purpose:

-lay out some basic fd theory -get some equations out there -talk about thresholding and residuals and mathematical models -explain how faults are limited in what they can capture -talk about some solutions to this, like learning models -talk about their downsides, like needing to have a lot of training data, and hardness to debug -lead into the higher-level analysis of correlation between faults, and my theories about how this can be effective

There is a rich body of literature related to telemetry visualization techniques and fault diagnosis. We borrowed insight and several visualization techniques from the literature. Cancro et al. developed useful techniques for packing large numbers of channels into a dense rectangular space [?], and Yairi et al. demonstrated ways to show change correlation between data channels [?], which were inspirations for our Global Correlation Matrix and Channel Correlation Vector. Simple fault detection methodology was adapted from Willsky [?].

2.1 A Section

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2.1.1 A Subsection

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2.2 Another Section

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Chapter 3

Correlative Analysis

Purpose:

-briefly introduce why I think correlative analysis is valuable -talk about some basic correlative theory and statistic analysis -lay out various correlation score techniques -talk about their limitations and some alternatives -choose what I think is most appropriate for this problem -lay out argument for PCC, perhaps

3.1 Correlation for Fault Analysis

3.1.1 Correlation Matrices

3.1.2 Cross-Correlative Leak Analysis

Isermann paper

Discussion of how this is using correlation between telemetry values to look for an understood fault state, rather than for data discovery (but it's still valuable!)

3.2 Common Correlation “Score” Techniques

When looking at two sets of data, it can often be valuable to reduce their interdependence (i.e., how much they change in sync with each other) into a single number, or “correlation coefficient.” This coefficient can be used as straightforward metric to determine correlation between sets of times series data. It may even be used as input into visualization algorithms to affect shading or even positioning, as we will see in later chapters.

3.2.1 Pearson Correlation Coefficient

The Pearson Correlation Coefficient (PCC), also known as the Pearson Product-Moment Coefficient, is a metric of the linear relationship between two sets of data. It is essentially a scaled covariance, defined as

$$\rho_{X,Y} = \frac{\text{cov}(X, Y)}{\sigma_X \sigma_Y} \quad (3.1)$$

where X and Y are two vectors of data (or, in the case of the telemetry data sets we examine in this paper, times series of values over time for two telemetry channels). The PCC gives a quantified measurement of the linear correlation between the two vectors, in the form of a value in the range of $[-1, 1]$, where 1 is a total positive correlation, -1 is a total negative correlation, and 0 is no correlation at all.

The Pearson Correlation Coefficient carries with it a few important assumptions:

- Samples have values that are interval or ratio variables (not ordinal or categorical)
- Sample pairs follow a bivariate normal distribution
- Sample pairs have a linear relationship (or, at least, these are the type of relationships you wish to see)

If the data doesn't fit the assumptions above, one of the two rank correlation coefficients discussed below may be more appropriate.

3.2.2 Spearman Rank Correlation Coefficient (ρ)

The Spearman Rank Correlation Coefficient, or Spearman's rho, is a type of correlation coefficient, which, like the PCC, seeks to quantify relationships between vectors of data, but which looks the ranking of variables within an ordering, rather than their linear relationship. This allows the coefficient to express relationship *monotonicity*, in order to be less dependent on linearity of relationships. It actually makes use of the PCC to do this, by calculating the PCC on the ranked data values.

3.2.3 Kendall Rank Correlation Coefficient (τ)

The Kendall Rank Correlation Coefficient, like Spearman's rho, seeks to capture non-linear dependence by using the ordered ranks of the argument variables as input to the algorithm.

3.3 Limitations of Traditional Correlative Techniques

There are many limitations to the three traditional correlative techniques above, and it's important to understand them, even if the ultimate decision will be to use one of these techniques. Some of the major limitations are described below.

3.3.1 Linearity Assumptions

The PCC algorithm, in particular

In contrast, the rank correlation methods

3.3.2 Multivariate Normal Distances vs. Elliptical Distances

3.3.3 Implied Causation

3.3.4 Alternatives to Correlation Score Techniques

3.3.5 Distance Correlation

3.3.6 Correlation Ratio

3.3.7 Brownian Covariance

3.3.8 Coefficient of Determination

3.3.9 Polychoric Correlation

Chapter 4

Visualization of Correlative Relationships

Purpose:

-talk about why we need to visualize correlative relationships in the first place -talk about challenges of visualization of correlation -talk about Z-scores for comparison and other traditional statistical methods -present corrgrams and their background and theory -talk about some popular applications of corrgrams and research -talk about extensions and the idea of animated corrgrams –don't get into the widgets/data reduction methods of corrgrams yet; I can do that later

4.1 Goals

4.2 Corrgrams

4.2.1 Background

4.2.2 Applications

4.2.3 Animated Corrgrams

Chapter 5

Case Study: Hakuto “Moonraker” Lunar Rover

In this section, we will discuss a motivating problem and platform on which to test some of the algorithms we’ve developed and assess their practicality.

5.1 HAKUTO Lunar XPRIZE Team

In the summer and autumn of 2015, research was performed at Tohoku University’s Space Robotics Lab (hereafter “SRL”), under the guidance of Professor Kazuya Yoshida, among others. This laboratory focuses on the research and development of robotic systems for space exploration and science missions.

One of the major sub-groups within SRL is the Hakuto Lunar XPRIZE team, a group of engineers who, working together with their promotional counterparts in Tokyo, have been working for several years on the core mission of sending a lunar rover to the Moon, traveling at least 500 meters, and sending back high-resolution and photos. Completing this mission would satisfy the requirements of the Google Lunar XPRIZE, an international lunar rover competition with a combined purse of \$30M USD [1].

As a secondary mission, Hakuto hopes to explore the interior of caves on the Moon, as precursor exploration to assess their feasibility as future human habitats. Recent high-resolution photography from JAXA’s Kaguya spacecraft, and from NASA’s Lunar Reconnaissance Orbiter, has confirmed that large “skylights” exist on the lunar surface leading into these caves [3], and Hakuto aims to land near enough to one of these skylights to make its exploration a possibility.

We decided that Hakuto’s four-wheeled “Moonraker” rover would be an excellent testbed against which to develop advanced fault analysis algorithms and visualization. Moonraker is a state-of-the-art micro-rover, developed over the past 5 years by the Hakuto team. During normal operation, Moonraker sends back status reports on 100 to 150 channels of telemetry data to its ground station on Earth, at a rate of once per second. This telemetry covers everything from IMU attitude data and temperature sensors readings to motor rotations, solar charge voltage, and communication metadata such as packets errors detected and radio signal strength.

See Figure 5.1 for a photo of Moonraker.



FIGURE 5.1: Hakuto’s Moonraker “Pre-Flight Model 2.” Photo by George Thomas Mendel.

5.2 Ground Station Interface

After I joined Team Hakuto, we began designing a new ground station software suite for the most recent version of the rover. The rover had been updated in several ways since the prior Pre-Flight Model, and many of its avionics, including its software, were updated and redesigned, breaking compatibility with the previous version of the ground

station software. We worked together to evaluate the current and future needs of the rover, and to redesign and reimplement software to optimally fit these needs.

Our discussions focused on optimizing performance, reliability, and maintainability of the software. The latter factor was of particular concern, given that the software was to be used and maintained in a university laboratory environment, with many students—some of them inexperienced in software engineering—potentially responsible for updating the software and adding new features. After evaluating a list of disparate choices, including C++ on Linux with the Qt framework and multi-platform JavaScript running in HTML5, we ultimately decided that the ideal choice would be the Unity Game Engine, for its high frequency of software updates, its active developer community, and its aerospace legacy within the NASA Jet Propulsion Laboratory [7].

5.2.1 Non-FDIR-Related Components

The focus of this paper is on the fault detective and correlative visualizations implemented within the ground station, so we will spend the bulk of the time focusing on this component. However, there were several non-FDIR-related components as well, briefly described below to provide context:

- *Numerical telemetry display*, to visually show the state of various sensors on subsystem boards (such as IMU accelerations, motor voltages, and board temperatures), as well as internal software metrics. Whenever possible, telemetry data was placed in semantically meaningful positions and groups, to improve discoverability.
- *Attitude display and visual tachometer*, to provide more intuitive visualizations of pitch, roll, and current wheel rotation rate (which mostly corresponded to vehicle speed).
- *Telemetry change indicators*, to point out data channels that have strong downward or upward trends over time.
- *Quad-camera display*, to display the most recent images and streaming video from the rover cameras.
- *Connectivity map*, to show the state of connectivity to various subsystems based on the elapsed time since packets from those subsystems had been received.
- *Immersive viewing*, allowing users to navigate the camera data in an embedded 3D mapping.

- ### 5.2.2 FDIR-Related Components

5.2.2.1 Threshold-based fault detection

MOBILITY

RPM	98	ROTATION	100	DISTANCE	0.15m	DISTANCE	0.15m	ROTATION	100	RPM	100
CURRENT	12mA	VOLTAGE	11mV	TIME	60s	TIME	60s	VOLTAGE	11mV	CURRENT	14mA
TEMP.	25°	PCB TEMP.	34°					PCB TEMP.	34°	TEMP.	55°

RPM	102	ROTATION	100	DISTANCE	0.15m	DISTANCE	0.15m	ROTATION	100	RPM	102
CURRENT	15mA	VOLTAGE	11mV	TIME	60s	TIME	60s	VOLTAGE	11mV	CURRENT	17mA
TEMP.	28°	PCB TEMP.	36°					PCB TEMP.	36°	TEMP.	54°

Pitch: -4.07° Roll: 0.76°

5.2.2.2 Fault alert panel

For safety, faults that have occurred need to be easily visible and understood by human operators. Towards this end, a highly visible, brightly colored alert panel was placed at the top of the screen seen by human operators. Each panel cell corresponds to a subsystem or other type of data grouping, and any issues with that grouping (i.e., faults that occur on monitored channels) will trigger a color change on that cell. Interacting

with the cell can give the user more information on the fault (see the next section for details). See Figure 5.3.



FIGURE 5.3: An alert panel monitors potential faults on various different subsystems, indicating any faults and their severity by color.

5.2.2.3 Detailed fault information

Ensuring human understanding of fault data is an essential part of the fault diagnosis and recovery process. As such, it's important to design a system where detailed information can be provided about individual faults that have occurred, while maintaining a high-level understanding of which systems are behaving anomalously. The system designed allows for this hierarchical organization of information. When high-level fault information is indicated in the “fault alert panel,” more concise information is provided in the “fault information panel,” including which anomalous data channels are contributing to the problem. The fault information is highly extensible, allowing for any other additional fault-related notes that system designers or operators would like to include for reference. This additional information, uncommon in traditional fault monitoring systems, accelerates the fault diagnosis problem by immediately pointing towards possible root causes. See Figure 5.4.

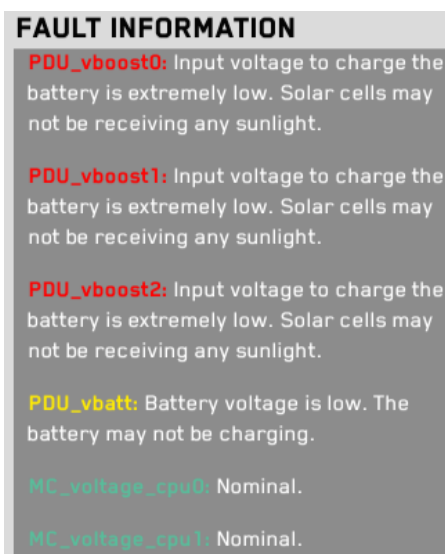


FIGURE 5.4: Information for monitored faults on a given subsystem.

5.2.2.4 Correlative Functionality

-start talking about correlation calculations –PCC for correlative analysis–give reasoning and background –corrgrams for visualization–give reasoning and background -give pseudocode and formulas for all calculations

5.3 Testing

5.3.1 Field Testing

5.3.2 Usability Testing

5.3.3 Data Discovery

5.3.4 Comparative Data Visualizations

Chapter 6

Intermediate Results and Reassessment

Purpose:

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6.1 A Section

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6.1.1 A Subsection

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Chapter 7

Dimensional Reduction and Visualization Improvements

Purpose:

7.1 Dimensional Reduction

7.1.1 Principal Component Analysis

Tharrault paper

Russell paper

7.2 Meta-Analysis

7.2.1 Out-of-Family Telemetry

Two NASA papers

7.2.2 Out-of-Family Correlations

7.3 Corrgram Enhancements and Dimensional Reduction

7.3.1 Smoothing and Time Adjustments

7.3.2 Ranked Filtering

7.3.3 Fault Filtering

7.3.4 Substring Filtering

7.3.5 Cross-System Filtering

7.3.6 Timelines

7.4 Two-Dimensional Graph Embeddings

7.4.1 Dependency Graphs

7.4.2 Time Curves

7.4.3 Snapshotted Network Diagrams

7.4.4

7.5 Time Curves

7.5.1

7.5.2

7.5.3

7.5.4

7.6 Multidimensional Scaling for Characterizing Correlation Families

7.6.1

7.6.2

Chapter 8

Results and Discussion

Purpose:

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Chapter 9

Conclusion

Purpose:

recap of intro:

Purpose:

-to lay out the basic idea of the paper -explain motivating problem of paper -briefly mention what aerospace faults are -say why they're hard to troubleshoot -explain a little bit about root cause analysis -talk about what I'm trying to do in the paper -which is to look at data connections, correlation, etc. on a real aerospace system to try to figure out how data discovery can best be achieved and how patterns can be found with math methods -these aren't easy to show, so also look into viz -implement for actual system -evaluate -reassess -make modifications to both math and viz -test again -find conclusions

Appendix A

An Appendix

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