Satellite Management Agent

by

Ulrich Louw

Thesis presented in fulfilment of the requirements for the degree of
Master of Engineering (Electronic Engineering)
in the Faculty of Engineering at Stellenbosch University

Supervisor: Dr HW Jordaan
Co-supervisor: Dr JC Engelbrecht

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Declaration

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Date: September 1, 2022

Abstract

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Opsomming

Skryf jou Afrikaanse opsomming hier.

Acknowledgements

The author wishes to acknowledge the following people and institutions for their various contributions towards the completion of this work:

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-
-

Table of Contents

Glossary

Something Description of that something.

Something Description of that something.

Something Description of that something.

List of Reserved Symbols

Symbols in this thesis conform to the following font conventions:		
A	Symbol denoting a **some general thing**	(Roman capitals)
$\mathcal{A}$	Symbol denoting a **some general thing**	(Calligraphic capitals)

Symbol	Meaning
$\times$	Symbol used to denote the multiplication operator
$\times$	Symbol used to denote the multiplication operator
$\times$	Symbol used to denote the multiplication operator
$\times$	Symbol used to denote the multiplication operator
$\times$	Symbol used to denote the multiplication operator

List of Acronyms

WISF: What It Stands For

WISF: What It Stands For

WISF: What It Stands For

List of Figures

List of Tables

List of Algorithms

CHAPTER 1

Introduction

Contents

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1.1 Background

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1.2 Informal problem description

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1.3 Research hypothesis

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1.4 Scope and objectives

The following objectives will be pursued in this project/thesis/dissertation:

I To *conduct* a thorough survey of the literature related to:

- (a) facility location problems in general,
- (b) models for the placement of a network of radio transmitters in particular,
- (c) the nature of parameters required to describe effective radio transmission, and
- (d) terrain elevation data required to generate an instance of the bi-objective radio transmitter location problem described in the previous section.

II To *establish* an suitable framework for evaluating the effectiveness of a given set of placement locations for a network of radio transmitters in respect of its total area coverage and its mutual area coverage.

III To *formulate* a bi-objective facility location model suitable as a basis for decision support in respect of the location of a network of radio transmitters with a view to identify high-quality trade-offs between maximising total coverage area and maximising mutual coverage area. The model should take as input the parameters and data identified in Objective I(c)–(d) and function within the context of the framework of Objective II.

IV To *design* a generic *decision support system* (DSS) capable of suggesting high-quality trade-off locations for user-specified instances of the bi-objective radio transmitter location problem described in the previous section. This DSS should incorporate the location model of Objective III.

V To *implement* a concept demonstrator of the DSS of Objective IV in an applicable software platform. This DSS should be flexible in the sense of being able to take as input an instance of the bi-objective radio transmitter location problem described in the previous section via user-specification of the parameters and data of Objectives I(c)–(d) and produce as output a set of high-quality trade-off transmitter locations for that instance.

VI To *verify* and validate the implementation of Objective V according to generally accepted modelling guidelines.

VII To *apply* the concept demonstrator of Objective V to a special case study involving realistic radio transmission parameters and real elevation data for a specified portion of terrain.

VIII To *evaluate* the effectiveness of the DSS and associated concept demonstrator of Objectives IV–VI in terms of its capability to identify a set of high-quality trade-off solutions for a network of radio transmitter locations.

IX To *recommend* sensible follow-up work related to the work in this project which may be pursued in future.

1.5 Research methodology

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1.6 Project/thesis/dissertation organisation

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CHAPTER 2

Literature Study

Contents

The implementation of FDIR on satellites have multiple complications with regards to the type of data generated by a satellite and the methodologies that can be implemented within the time and memory constraint of a cube-sat processor.

2.1 Anomaly Detection on Satellites

Various methodologies have been tested on different component of satellites. Therefore a summary of these research articles are provided in this section.

2.1.1 Analysis and Prediction of Satellite Anomalies

Wintoft et al. [33]

2.1.2 Agent-based algorithm for fault detection and recovery of gyroscope's drift in small satellite missions

To ensure that the ADCS of satellites are autonomous every aspect of the control must be able to recover from faults. Carvajal-Godinez et al. [5] developed an algorithm to evaluate the control of a gyroscope and detect whether drifting exists. If drifting is detected the another algorithm is deployed to ensure the recovery of the gyroscope drift by updating the error state vector.

2.1.3 Fault isolation of reaction wheels onboard three-axis controlled in-orbit satellite using ensemble machine learning

[26]

2.1.4 Fault tolerant control for satellites with four reaction wheels

[22]

2.1.5 Innovative Fault Detection, Isolation and Recovery Strategies On-Board Spacecraft: State of the Art and Research Challenges

[32]

2.1.6 Machine learning methods for spacecraft telemetry mining

[18]

2.1.7 Machine learning techniques for satellite fault diagnosis

[19]

2.2 Statistical Methods

2.2.1 Pearson Correlation

Vectors of certain sensors are highly correlated. For instance the vector of the earth sensor is highly correlated since the magnitude of the vector remains more or less constant. To detect anomalies the correlation of vectors can be measured and with a specified threshold the correlation can be indicated as a anomaly or nor.

The squared Pearson correlation coefficient (SPCC) for vectors depicted as

$$a = [a_1, a_2, \dots, a_L]^T,$$
$$b = [b_1, b_2, \dots, b_L]^T,$$

is defined as [3]

$$\rho^2(a, b) = \frac{E^2(a, b)}{E(a^T a)E(b^T b)}. \tag{2.1}$$

The correlation coefficient is proven to be constraint as

$$0 \le \rho \le 1, \tag{2.2}$$

where $\rho = 1$ is perfect linear correlation.

2.2.2 Variance

Within a sequential data sample of the satellite, the variance of the variables should be within a given threshold if the satellite is in a stable condition. The variance of the data sample is defined as

$$S^2 = \frac{\sum(x_i + \bar{x})^2}{n - 1} \tag{2.3}$$

where x defines the variable within the dataset.

2.2.3 Kalman-Filter

The Kalman-filter application would require the state-space matrices to be provided in the log file.

2.2.4 Multivariate Guassian Distribution

The assumption that the error of our data is generated with a Guassian distribution with a specific mean, μ, and variance, σ^2, provides the opportunity for using multi-variate Gaussian distribution to determine the probability of a data-sample within a dataset.

$$\mu_j = \frac{1}{m} \sum_{i=1}^{m} x_j^{(i)} \tag{2.4}$$

$$\sigma_j^2 = \frac{1}{m} \sum_{i=1}^{m} (x_j^{(i)} - \mu_j)^2 \tag{2.5}$$

$$p(x) = \prod_{j=1}^{n} \frac{1}{\sqrt{2\pi}\sigma_j} exp(-\frac{(x_j - \mu_j)^2}{2\sigma_j^2}) \tag{2.6}$$

For multi-variate Guassian distribution [13].

$$\sum = \frac{1}{m} \sum_{i=1}^{m} (x^{(i)} - \mu)(x^{(i)} - \mu)^T \tag{2.7}$$

$$p(x) = \frac{1}{(2\pi)^{\frac{n}{2}} |\sum|^{\frac{1}{2}}} exp(-\frac{1}{2}(x - \mu)^T \sum^{-1} (x - \mu)) \tag{2.8}$$

The Anomalies will be classified based on probabilities smaller than a given threshold $p(x) < \epsilon$.

Algorithm 2.1: Multi-variate Guassian Distribution Algorithm

Input : Data sample from satellite orbit.
Output: Whether dataset contains anomaly.

```
Determine feature vectors x_i
Determine threshold probabilty, ϵ
Calculate μ_j with Eq 2.4
Calculate σ_j with Eq 2.5
Calculate p(x) with Eq 2.6
if p(x) < ϵ then
    Anomaly = True
else
    Anomaly = False
```

2.2.5 Kullback-Leibler Divergence

The Kullback-Leibler divergence quantifies the difference between two probability density functions, denoted as $p(x)$ and $q(x)$ [17]. Satellites are systems that are predictable within a time-series. The divergence between two sequential data buffers from the satellite will have a very similar probability distribution. Therefore calculating the difference between two datasets can be used to detect an anomaly based on a given threshold.

The difference between the probability distributions from datasets, a and b, in Figure 2.1 cannot simply be calculated as the difference in the mean or the difference in the variance. To overcome this, the divergence between the two distributions can be calculated. Intuitively a point x with a high probability in the dataset a should have a high probability in the dataset b if the two datasets have a small divergence.

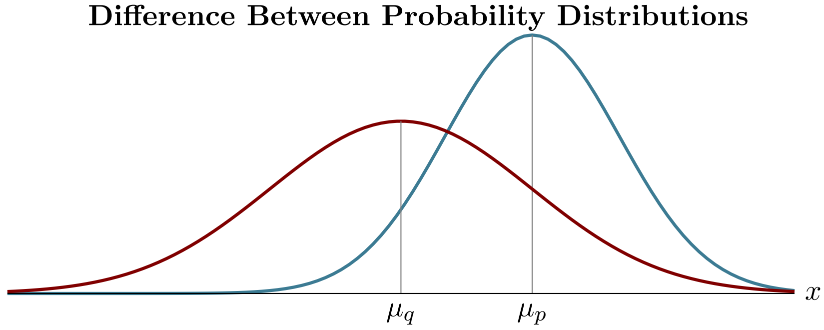


FIGURE 2.1: *Guassian Distributions*

The divergence can be expressed as

$$KL(P||Q) = \int p(x) \log \left(\frac{q(x)}{p(x)} \right) dx. \tag{2.9}$$

2.2.6 Canonical Correlation Analysis

Due to the orbital nature of satellites there exist a correlation between various sensors. For instance the sun sensor, magnetometer and earth sensor are correlated based on the desired orientation and orbit of the satellite. This correlation might not be of linear nature, but with non-linear correlation methods such as kernel canonical correlation the correlation can be measured.

However, canonical correlation provides the measure of correlation between a multi-dimensional variable with another multi-dimensional variable. Although this seems profitable for satellite fault detection, it will only be applicable for each the comparison between individual sensors. This will indicate the non-linear correlation of the sun sensor with regards to the magnetometer. The problem however, according to Chen et al. [8] is to, determine the appropriate threshold for which to classify a fault. Chen et al. [8] proposed a method for determining the appropriate threshold on page 5, algorithm 1. [14] [34]

Python - Pyrcca package

K-means-based

Guassian Mixture Model

Just-In-Time-Learning

[7]

2.3 Feature Extraction

To https://towardsdatascience.com/feature-extraction-techniques-d619b56e31be

2.3.1 Prony's Method

2.3.2 Convolutional Networks

2.3.3 K-means Clustering

K-clustering: Clustering multiple points with similar features.

2.3.4 Principal Component Analysis

[10] [12]

2.3.5 Partial Least Square

2.3.6 Independent Component Analysis

2.3.7 Locally Linear Embedding

2.3.8 Linear Discriminant Analysis

2.3.9 Autoencoder

2.3.10 t-Distributed Stochastic Neighbor Embedding

2.4 Supervised Learning

Supervised learning consists of models that are trained on labelled data. This is not a problem with simulation, but with the real data, it is a problem and to provide tests on the real data to label it must be proficient. If unsupervised learning and statistical methods are not sufficient in their accuracy, a method for labelling the real data must be provided.

2.4.1 Random Forests

[28, 24, 25]

2.4.2 Long Short Term Memory

Time-series data: LSTM or DLSTM

2.4.3 Support Vector Machines

Support Vector Machines

2.4.4 Naive Bayes

Naive Bayes

2.4.5 K-nearest neighbours

K-nearest neighbours

2.4.6 Artificial Neural Networks

Artificial Neural Networks

2.5 Unsupervised Learning

Density-based, distance, Clustering

2.5.1 Isolation Forests

This unsupervised learning methods is based on the principle of isolating data points by slicing the data with random conditions [31]. The data is randomly split into specified sample sizes with a randomly selected dimension and a randomly selected cut-off value. For each sample size the data must be split until each data point within the sample is isolated from all other data points. Training of a single tree is completed when all the data points are isolated and this training must be repeated for all the data samples, however many are predefined.

The distance measured from the first split the *tree top* to the isolated data point is used to determine whether a data point is anomalous or not [16]. The logical reasoning for support of this algorithm is that data points which are non-anomalous will be more closely related and hence have more splits to separate the data points until isolation is achieved. Therefore, the distance from the tree top for non-anomalous data points will be longer than anomalous data points which will have a shorter distance from the tree top. Therefore non-anomalous data points are closer to the *root*.

Figure 2.2 demonstrates the splitting of the data points until isolated. Each split or *branch* only splits the data into two groups. After training multiple trees, a single data point is "sent through the forest" and the distance from the tree top for each tree is calculated and the average of all the trees are used to calculated the average distance for the data point. Using a threshold for the distance, the data point is classified as anomalous or not.

The anomaly score is calculated with Eq 2.10

$$s(x, n) = 2^{-E(h(x))/c(n)} \tag{2.10}$$

where $E(h(x))$ is the average value of the distance measured from the tree top for a single data point in all the trees [16] and n is the size of a data sample used to train a single tree. For the distance to be normalized, $c(n)$ — the mean distance from the tree top in an unsuccessful search in a *Binary Search Tree* (BST) — is used and is calculated as

$$c(n) = 2H(n-1) - \frac{2(n-1)}{n}. \tag{2.11}$$

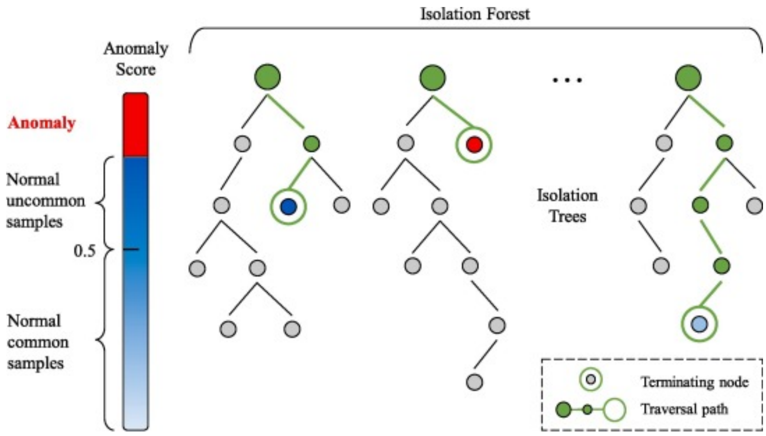


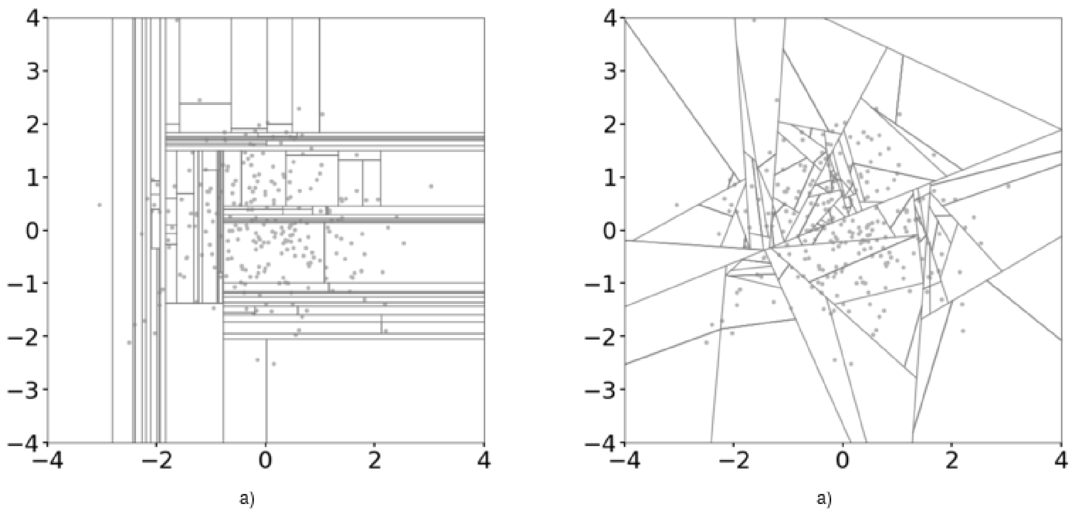
FIGURE 2.2: *Isolation Forests [6]*

$H(i)$ in Eq 2.11 is the harmonic number and is estimated with Euler's constant as

$$H(i) \approx ln(i) + 0.5772156649. \tag{2.12}$$

Isolation Forests, however have multiple issues, since it splits data in rectangles as seen in Figure 2.3(a). This is due to the slicing algorithm selecting a feature, x and a cut-off value, v. Consequently, the data is either split vertically or horizontally — if seen as a two dimensional dataset. This split method is unable to categorise complex data structures. These issues however are addressed by Hariri et al. [16] and led to the *Extended Isolation Forest* algorithm.

The extended isolation forest algorithm generalises the isolation forest algorithm by applying a slope to each slice. Data points are therefore divided into two groups depending on the "side" of the plane or slice as seen in Figure 2.3(b).



(a) *Isolation Forest Slicing example* (b) *Extended Isolation Forest Slicing example*

FIGURE 2.3: *The slicing of Isolation Forest vs Extended Isolation Forest*

It is evident that applying an angle of 0° to all the slices the general algorithm of the extended isolation forest produces the standard isolation forest algorithm where planes or slices are perpendicular to the axis of the randomly selected feature, x.

2.5.2 Local Outlier Factor

Most algorithms for anomaly detection are based on a metric which accounts for the entire dataset [4]. However, many anomalies are identifiable in relation to the local neighbourhood of data points and not the overall dataset. Therefore, Breunig et al. [4] developed the local outlier factor LOF algorithm that provides a measure of a data point's "outlierness". This implies that a data point is not classified as an anomaly or not, but a local outlier factor is calculated to determine how much a data point is distantiated from it's k-nearest neighbours. This is clearly demonstrated in Figure 2.4 where the data points which are clustered together have smaller LOF's than data points which are removed from the highly dense areas.

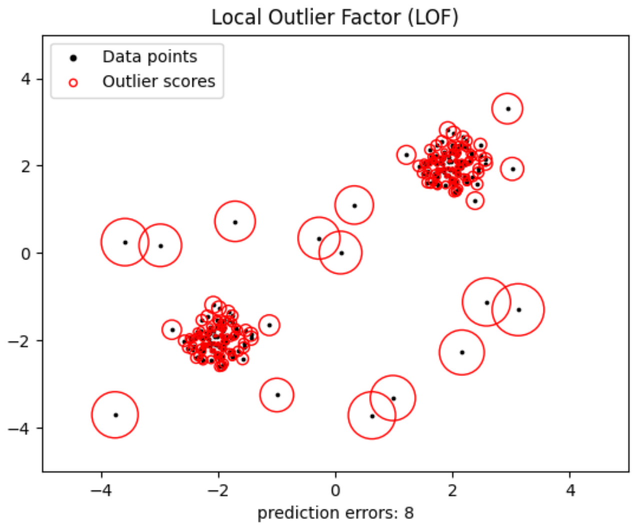


FIGURE 2.4: *LOF measure*

To calculate the LOF, the k-distance must be calculated and also the local reachability density lrd. The k-distance, is the k^{th} ranked $distance(o, p_i)$. Where $distance(o, p_i)$ is the distance between data point o and any data point p_i, with $i \in N$, where N is the number of data points within the dataset with a minimum value of $MinPts$. To reduce fluctuations in the $distance(o, p_i)$ the distance between o and p_i is replaced with

$$max\{distance(o, p_i), k\text{-distance}\} \tag{2.13}$$

and will henceforth be referred to as the reachability distance [4]. The lrd of a data point, p, is calculated as

$$lrd_{MinPts}(p) = 1/\left(\frac{\sum_{o \in N_{MinPts}(p)} reachdist_{MinPts}(p, o)}{|N_{MinPts}(p)|}\right) \tag{2.14}$$

and denotes "the inverse of the average reachability distance based on the $MinPts$-nearest neighbours of the p" — Breunig et al. [4]. Eq 2.14 enables the calculation for the LOF of point p as shown in Eq 2.15

$$LOF_{MinPts}(p) = \frac{\sum_{o \in N_{MinPts}(p)} \frac{lrd_{MinPts}(o)}{lrd_{MinPts}(p)}}{|N_{MinPts}(p)|} \tag{2.15}$$

The rule of thumb for detecting an outlier is that when the LOF is larger than 1, then the point is considered an outlier with respect to its neighbourhood. This however is not fixed and the threshold can be changed depending on the application.

This method is aimed at producing a measure of the ”outlierness” of a data point within a local neighbourhood and not for all the data points. This method will thus be implemented for the satellite anomaly detection, since it will detect anomalies within the two neighbourhoods produced by the eclipse during orbit. This method will also be able to detect measurements of earth sensors, sun sensors and magnetometers that drastically change from the previous orbital data. For example in Fig **??** it is evident that the LOF will be comparatively larger than the rest of the data points.

2.5.3 Kernel Adaptive Density-based

Kernel adaptive density-based: Is an algorithm that uses the density factor of a data point relative to other data points to determine whether the data point is an outlier or not.

2.5.4 Loda

Loda: Is a fast and efficient anomaly detection algorithm that used histograms to evaluate data points to determine whether a data point is an outlier. Loda is an on-line method and not a batch method.

2.5.5 Robust-kernel Density Estimation

Robust-kernel density estimation

2.6 Reinforcement Learning

Active Anomaly detection with meta-policy (Meta-AAD) is a deep reinforcement learning approcah that is based on the actor-critic model. The agent must query data points within the given dataset (where the queried point is the data top 1 data point). The query is given to a human

2.7 Summary

CHAPTER 3

Simulation

Contents

3.1 Satellites

The focus of this thesis is on small satellites and more specifically cubesats. For the simulation of the ADCS of the satellite [2, 21, 23] were referenced during the development of the satellite. The simulation was developed in Python to simulate the dynamics and kinematics during a satellite orbit.

The faults for the subsystems are also developed within the simulation and will be discussed within this chapter.

3.2 ADCS

3.3 Typical Faults

For the simulation of the satellite and the induced faults to train and test various anomaly detection methodologies a database of typical faults is required. Tafazoli [30] made a study of the percentage of failure per subsystem.

Faults

The occurrence of a fault depends on the reliability of that equipment. Guo et al. [15] studied the reliability of small satellites and calculated the parameters for the Weibull distribution based on real data. A set of typical faults for the ADCS is shown in Table **??**.

Internal Faults					
Fault classes	**Failure rate per hour**	**Fault causes**	**References**	**Possible effect**	**Possible permutations**
Reaction wheels	2.5E-7 [29]	Reaction wheel electronics fail	[1] [20]	Does not respond to control inputs	Momentum remains the same or decreases slightly due to friction
		Overheated reaction wheel	[33]	Decrease in speed	1% of initial speed per second
		Catastrophic failure (cause unknown)	[9]	Stops rotating	0
		Increase in rotation speed (Unknown cause)	Gerhard Janse van Vuuren	Wheel speed increases	Between 90-100% of maximum wheel speed
Magnetorquers	8.15E-9 [29]	Polarities are inverted	[11]	Incorrect rotation	
Magnetometers	8.15E-9 [29]	Unknown	Gerhard Janse van Vuuren	Stops reacting	Provides no feedback or the output remains constant
		Magnetometers and magnetorquers interfered with each other	[20]	Noise on magnetometers and noise on control of magnetorquers	Between x3 and x5 times the normal noise magnitude Guassian distribution
Earth Sensor	-	Unknown	[27]	Noisy Earth Sensor effected pointing accuracy	Between x5 and x10 times the normal sensor noise based on Guassian distribution
Sun sensor	-	Cross-wired during installation	[11]	Erroneous measurements	Uniform random values
		Unknown	[20]	Sun sensor fails	output is 0
Star tracker	-	Shutter on star tracker is closed	[11]	Star tracker fails	output is 0
Overall control	-	Incorrect control law or variation thereof	Gerhard Janse van Vuuren	Angular velocity suddenly increases or decreases or oscillation results	Increase to 75 - 100% Decrease to 0 - 25% Oscillates
Common data transmission errors	-	Sign flip	[11]	Processor-based	Processor outputs and/or inputs experience a sign flip
		Bit flip	N/A		Processor outputs and/or inputs experience a bit flip flip
		Insertion of zeros	[20]		Processor outputs and/or inputs experience an insertion of a zero
Possible sensors errors	-	Unknown	N/A	High sensor noise	Between x5 and x10 times the normal sensor noise based on Guassian distribution

CHAPTER 4

Implementation of Methods on Actual Satellite

Contents

4.1 Isolation Forests

A trained network will be developed from simulation data or the data generated during the first few orbits of a satellite. Afterwards the anomaly score will be calculated for a data point and based on a given threshold, the data point will be flagged as an anomaly or not.

CHAPTER 5

Conclusion

Contents

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5.1 Project/thesis/dissertation summary

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5.2 Appraisal of project/thesis/dissertation contributions

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5.3 Suggestions for future work

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5.4 What the student has learnt during this project

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APPENDIX A

Project Timeline

The expected timeline is given in Figure A.1 in Gantt-chart form.

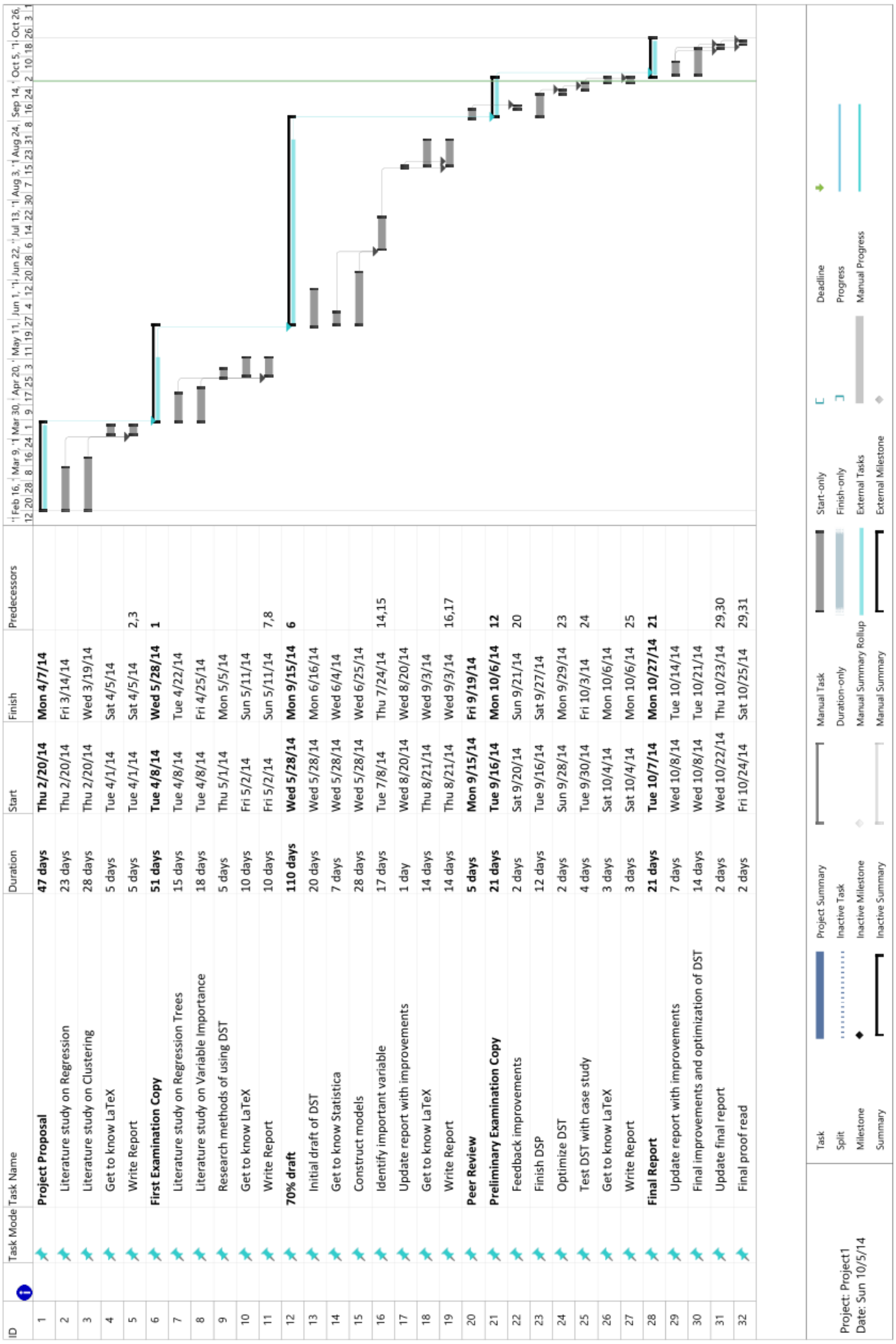

FIGURE A.1: *Expected timeline in Gannt-chart form.*

APPENDIX B

Data

Data related to the Case Study in Chapter 5 are presented in Table B.1.

		this goes across 6 columns					
		col a	col b	col c	col d	col e	col f
this is sideways, and goes across six rows	row 1						
	row 2						
	row 3						
	row 4						
	row 5						
	row 6						

TABLE B.1: *Type full caption here.*