Satellite Management Agent

by

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

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Co-supervisor: Dr JC Engelbrecht

September 2022

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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-
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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, Lundstedt, Eliasson, and Kalla [26]

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, Guo, and Gill [4] 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

[21]

2.1.4 Fault tolerant control for satellites with four reaction wheels

[19]

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

[25]

2.1.6 Machine learning methods for spacecraft telemetry mining

[15]

2.1.7 Machine learning techniques for satellite fault diagnosis

[16]

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

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

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 [11].

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

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

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 $q(x)$ [14]. 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.

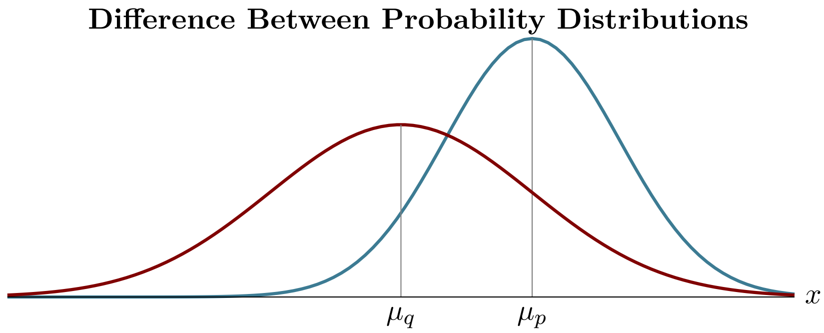

FIGURE 2.1: *Guassian Distributions*

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, Ding, Peng, Yang, and Gui [5] is to, determine the appropriate threshold for which to classify a fault. Chen, Ding, Peng, Yang, and Gui [5] proposed a method for determining the appropriate threshold on page 5, algorithm 1. [12] [27]

Python - Pyrcca package

K-means-based

Guassian Mixture Model

Just-In-Time-Learning

[6]

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 Principal Component Analysis

[8] [10]

2.3.4 Partial Least Square

2.3.5 Independent Component Analysis

2.3.6 Locally Linear Embedding

2.3.7 Linear Discriminant Analysis

2.3.8 Autoencoder

2.3.9 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 Long Short Term Memory

Time-series data: LSTM or DLSTM

2.4.2 Support Vector Machines

Support Vector Machines

2.4.3 Naive Bayes

Naive Bayes

2.4.4 K-nearest neighbours

K-nearest neighbours

2.4.5 Artificial Neural Networks

Artificial Neural Networks

2.5 Unsupervised Learning

Density-based, distance, Clustering

2.5.1 Random Forests

2.5.2 Isolation Forests

Isolation Forests: Are based on the pIndependentrinciple of randomly dividing a dataset. The data points that are closer to the root of the division is anomalies. Isolation forest are small in memory and are fast in computing anomalies.

2.5.3 Local Outlier Factor

LOF: Local outlier factor is a method of determining how much an outlier a specific data point is relative to a neighbourhood of other data points.

2.5.4 K-means Clustering

K-clustering: Clustering multiple points with similar features.

2.5.5 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.

2.5.6 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.

2.5.7 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, 18, 20] 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 [24] made a study of the percentage of failure per subsystem.

Faults

The occurrence of a fault depends on the reliability of that equipment. Guo, Monas, and Gill [13] 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 [23]	Reaction wheel electronics fail	[1] [17]	Does not respond to control inputs	Momentum remains the same or decreases slightly due to friction
		Overheated reaction wheel	[26]	Decrease in speed	1% of initial speed per second
		Catastrophic failure (cause unknown)	[7]	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 [23]	Polarities are inverted	[9]	Incorrect rotation	
Magnetometers	8.15E-9 [23]	Unknown	Gerhard Janse van Vuuren	Stops reacting	Provides no feedback or the output remains constant
		Magnetometers and magnetorquers interfered with each other	[17]	Noise on magnetometers and noise on control of magnetorquers	Between x3 and x5 times the normal noise magnitude Guassian distribution
Earth Sensor	-	Unknown	[22]	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	[9]	Erroneous measurements	Uniform random values
		Unknown	[17]	Sun sensor fails	output is 0
Star tracker	-	Shutter on star tracker is closed	[9]	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	[9]	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	[17]		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

Conclusion

Contents

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4.1 Project/thesis/dissertation summary

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4.2 Appraisal of project/thesis/dissertation contributions

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4.3 Suggestions for future work

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4.4 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.

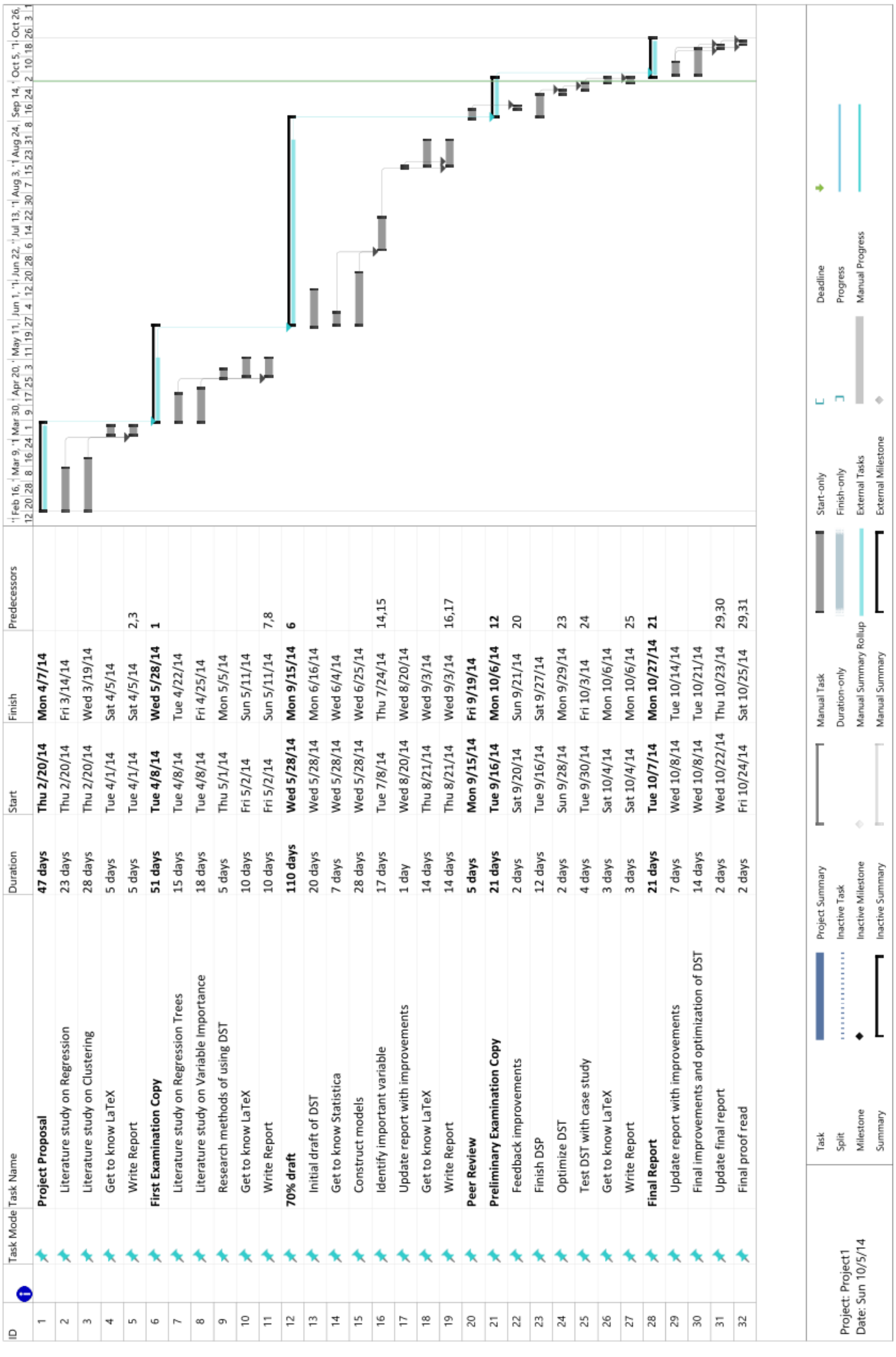

FIGURE A.1: *Expected timeline in Gannt-chart form.*

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.*