COMPUTER-AIDED REAL-TIME KINEMATIC GLOBAL POSITIONING SYSTEM POSITIONING TECHNIQUE FOR DEFORMATION MEASUREMENT AND ANALYSIS

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To my beloved family who unselfishly supported me throughout the entire endeavour and those who inspired me. They make it all worthwhile.

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ABSTRACT

Scientific justification and technical feasibility of using Real-Time Kinematic Global Positioning System (RTK-GPS) positioning as the technique in recording the responses (in term of coordinate / position) of deformable structures have been proven very promising. The major advantages are the real-time measurement (either online or offline) and direct measurement of relative displacement. Nevertheless, the research, through the sampled data, shows the need of additional steps to handle the possible errors in direct employment of manufacturers' RTK positioning solution for deformation monitoring. In addition, most of the further applications such as online, automated, continuous, etc., however, have to be self customized and developed. The sampled data comprise short baseline (1.8km, collected in Universiti Teknologi Malaysia) and medium length baseline (27.7km, provided by Geodesy Section, Department of Survey and Mapping, Malaysia). The research thus suggests an additional approach for RTK positioning integrity monitoring and deformation detection. The RTK positioning integrity monitoring includes error identification, outlier filtering and reference station stability checking. The essence of the approach is the Normal Point technique as well as the Local Threshold and Global Threshold. Reference for Local Tolerance and Global Tolerance are also discussed. To get the additional approach running more efficiently in one single system, prototype software, Sparrow, was developed in Visual Basic environment and by deploying the Trimble bundled software, which are Trimble GPS Configurator and Trimble Reference Station. Sparrow is also developed to serve for online, automated, and continuous deformation monitoring. At the same time, Sparrow provides real-time and past result presentation in both graphical and numerical format. Three tests are taken to verify the applicability of Sparrow and the validity of Normal Point.

ABSTRAK

Kajian mengenai penggunaan Sistem Penentududukan Global Kinematik Masa Hakiki (*Real-Time Kinematic Global Positioning System, RTK-GPS*) untuk mencatat tindakbalas (dalam bentuk koordinat / kedudukan) struktur yang mengalami deformasi telahpun banyak dibuktikan kemunasabahannya. Kelebihan utamanya adalah pencerapan masa hakiki (sama ada secara *online* ataupun *offline*) dan pencerapan pergerakan relatif secara langsung. Walau bagaimanapun, dengan data sampel, kajian ini menunjukkan keperluan langkah tambahan untuk mengendali selisih yang mungkin wujud dalam penyelesaian secara langsung penggunaan RTK daripada pengilang (*manufacturer*) untuk pemantauan deformasi. Tambahan pula, kebanyakan aplikasi lanjutan seperti *online*, automatik, berturutan (*continuous*), dan sebagainya perlu dicorak dan dibangunkan sendiri. Data sampel itu merangkumi garis dasar pendek (1.8km, dicerap di Universiti Teknologi Malaysia) dan garis dasar sederhana panjang (27.7km, dibekalkan oleh Seksyen Geodesi, Jabatan Ukur dan Pemetaan Malaysia). Oleh itu, kajian ini mencadangkan satu kaedah tambahan untuk pemantauan integriti penentududukan RTK dan pengesanan deformasi. Pemantauan integriti penentududukan RTK merangkumi pengenalpastian selisih, penurasan selisih kasar, dan pemeriksaan kestabilan stesen rujukan. Kelebihan kaedah tambahan tersebut adalah teknik Titik Normal dan Had Global serta Had Lokal. Rujukan untuk Toleransi Global dan Toleransi Lokal juga dibincangkan. Untuk mengendali kaedah tambahan itu dengan lebih efisien dalam satu sistem tunggal, perisian prototaip, Sparrow, telah dibangunkan dalam environmen Visual Basic dan mempergunakan perisian sediaada dalam Trimble iaitu Trimble GPS Configurator dan Trimble Reference Station. Sparrow juga dibangunkan untuk pemantauan deformasi yang bertujuan *online*, automatik, dan berturutan. Di samping itu, Sparrow memberikan persembahan keputusan masa hakiki dan lepas dalam bentuk grafik dan numerikal. Tiga ujian telah diambil untuk mengesahkan penggunaan Sparrow dan Titik Normal.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ASNT	American Society for Nondestructive Testing
C/A-code	Coarse/Acquisition Code
CC	Control Centre
CRS	Core Reference Station
CSP	Control Station Processing
CW	Continuous Wave
DoD	United States Department of Defence
DOP	Dilution of Precision
FBG	Fiber Bragg Grating
FDD	Frequency Domain Decomposition
FEM	Finite Element Method / Modelling
FFT	Fast Fourier Transformation
FIG	International Federation of Surveyors
GGA	GPS fix information
GPS	Global Positioning System
GT	Global Threshold
LAN	Local Area Network
LSE	Least Squares Estimation
NP	Normal Point
InSAR	Interferometric Synthetic Aperture Radar
IWST	Iterative Similarity Weighted Transformation
JUPEM	Department of Survey and Mapping, Malaysia
LT	Local Threshold
LGT	Lower Global Threshold
LLT	Lower Local Threshold
MIMO	Multiple Input - Multiple Output
MINT	Malaysian Institute for Nuclear Technology Research

NAVSTAR	Navigation Satellite Time and Ranging
NDT	Non-Destructive Testing
NMEA	National Marine Electronics Association 0183 Standard
NP	Normal Point
OP	Original Point
OTF	On-the-Fly
P-code	Precision code
PRN	Pseudo-Random Noise
PRC	Pseudo-Range Correction
RF	Radio Frequency
RRS	Reserved Reference Station
RTK	Real-Time Kinematic
SHM	Structural Health Monitoring
SPS	Standard Position Service
TCP/IP	Transmission Control Protocol / Internet Protocol
TGO	Trimble Geomatics Office
TPS	Terrestrial Positioning System
TRS	Trimble Reference Station
TSIP	Trimble Standard Interface Protocol
UERE	User Equivalent Range Error
UHF	Ultra High Frequency
UGT	Upper Global Threshold
ULT	Upper Local Threshold
UM	Usage Monitoring
UTC	Universal Time Coordinated
USACE	United State Army Corps of Engineers
VBA	Visual Basic for Applications
VHF	Very High Frequency
VNC	Virtual Network Computing
WG 6.1	Working Group 6.1 on Deformation Measurements and Analysis
WGS84	World Geodetic System 1984

LIST OF SYMBOLS

n_o	-	Fundamental natural frequency or period of a building
D	-	Base direction (in meters) in the direction of motion considered of the building
H	-	Height of the building (in meters)
C	-	Centre of mass of the earth
R	-	Position vector of the antenna to seek
r	-	Known position vector of satellite
ρ	-	True range from transmission at satellite to reception at receiver or antenna
y	-	Propagation of electromagnetic wave from the satellite to the receiver
A	-	Signal amplitude
k	-	Propagation wavenumber related to the free space wavelength
t	-	Elapsed time measured from the instant of transmission at the satellite
x	-	Distance travelled of the electronic wave from the satellite to the receiver
ω	-	Radian frequency
ϕ	-	Bias term
f_o	-	Fundamental frequency of GPS signal
p	-	Measured pseudo-range
c	-	Velocity of light
dt	-	Offset of the satellite clock from GPS time
dT	-	Offset of the receiver clock from GPS time
d_{ion}	-	Ionospheric delay
d_{trop}	-	Tropospheric delay
Φ	-	Measured carrier phase in length units
N	-	Unknown cycle count

λ	-	Wavelength
σ_o	-	Measurement accuracy
σ	-	Positioning accuracy
R_E	-	Range error due to clock instability / timing biases
T_O	-	Time offset
D_C	-	Dry term range contribution in zenith direction in meters
P_O	-	Surface pressure in millibar (mb)
T_L	-	Local tolerance
T_G	-	Global tolerance
N	-	Meridian arc distance from reference station (of user-defined coordinate system used in Sparrow)
E	-	Arc distance along the parallel latitude from reference station (of user-defined coordinate system used in Sparrow)
h	-	Ellipsoidal height of antenna (of user-defined coordinate system used in Sparrow)
ϕ	-	Latitude of geodetic coordinate system
λ	-	Longitude of geodetic coordinate system
H	-	Antenna altitude of geodetic coordinate system
N_{geoid}	-	Geoidal separation
S_ϕ	-	Meridian arc distance
S_λ	-	Arc distance along the parallel latitude
R_M	-	Radius of curvature in meridian
R_N	-	Radius of curvature in the prime vertical

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

Numerous accidents or disasters associated with large construction projects and natural events in the past have cost not only the great loss financially but also the lives that eternally embedded the great pain in the memory of their beloved family and friends. These horrendous tragedies include

(i) Sultan Abdul Halim Ferry Terminal Bridge collapse (July 31, 1988),
(ii) Highland Towers Condominium collapse (December 11, 1993),
(iii) Tsunami induced by the Indian Ocean earthquake (December 24, 2004), and
(iv) many other landslides, tremors as well as sudden collapse of the floor of a building during construction.

Further information on the abovementioned tragedies can be acquired at Wikipedia, (the free encyclopedia) and the study, entitled *Non-Destructive Testing of Concrete and Civil engineering Structures*, carried out by Malaysian Institute for Nuclear Technology Research (MINT). Besides, questions on whether our buildings are able to withstand the tremors have also been raised by the recent aftershocks caused by the earthquakes that struck the region. Further information on the discussion of the aftershocks can be reached at Property Times, the New Straits Times (2006).

These tragedies and aftershocks have awakened the public awareness and concern of the structure safety as well as natural event. Also, the need of monitoring has been called to serve as the alarm system or early-warning system. According to aforementioned study carried out by MINT, it was reported that amendment had been made to Street, Drainage and Building Act 1974 (Act 133) as a follow up of the Highland Towers tragedy. The act requires that after every ten years all high-rise building of more than five floors must be inspected for their safety before the renewal of certificate of fitness can be made. The Section 85_A of the act is attached in Appendix A.

In usual practices, the non-destructive testing (NDT) or structural health monitoring (SHM) will be implemented to assess the damage in structure and examine the integrity of the structure in order to come to a conclusion of the useful life or serviceability of the structure. In general, NDT and SHM hold a same role which is to ultimately guarantee the safety of the public. A brief introduction on NDT as well as SHM and damage is given in the following.

The American Society for Nondestructive Testing (ASNT) define the NDT as comprising those test methods used to examine an object, material or system without impairing its future usefulness. The term is generally applied to nonmedical investigations of material integrity. Non-destructive testing is concerned in a practical way with the performance of the test piece, such as, how long may the piece be used and when does it need to be checked again. The British Institute of Non-Destructive Testing define the NDT as the branch of engineering concerned with all methods of detecting and evaluating flaws in materials of that the flaws can affect the serviceability of the material and structure.

Based on *A Review of Structural Health Monitoring Literature: 1996-2001*, SHM is defined as the process of implementing a damage detection strategy for aerospace, civil, and mechanical engineering infrastructure. Usage monitoring (UM) attempts to measure the inputs to and responses of a structure before damage so that regression analysis can be used to predict the onset of damage and deterioration in structural condition (further discussion on the inputs to and responses of structure is continued in Section 2.3.2. Prognosis is the coupling of information from SHM, UM, current environmental and operational conditions, previous component and system level testing, and numerical modelling to estimate the remaining useful life of the system (Sohn et al., 2003). Also, according to *Summary Report on the first*

International Workshop on Structural Health Monitoring, the essence of SHM technology is to develop autonomous built-in systems for the continuous real-time monitoring, inspection, and damage detection of structures with minimum labour involvement (Harb, 2005).

In the most general terms, damage can be defined as changes introduced into a system that adversely affects its current or future performance. Implicit in this definition is the concept that damage is not meaningful without a comparison between two different states of the system, one of which is assumed to represent the initial, and often undamaged, state. On the study of damage identification in structural and mechanical systems, the definition of damage therefore will be limited to changes to the material and / or geometric properties of these systems, including changes to the boundary conditions and system connectivity, which adversely affect the current or future performance of these systems (Sohn et al., 2003). Some of the examples of damage are shown in the Table 1.1 below.

Table 1.1: Example of damage.

Damage	Change
Crack	Stiffness change
Scour	Boundary condition change
Weight loss	Mass change
Joint loosening	Connectivity change

However, to have the comprehensive diagnosis of the structure health or prognosis of damage in detail, there are a number of different measurements that have to be made for instance (but are not limited to) strain, acceleration, temperature, transmission and displacement. Further classification on the measurement is discussed in Section 2.3.2 (Ad-Hoc Committee of FIG, 2001; Sohn et al., 2003). Nevertheless, the displacement measurement is the main concern of this thesis.

Basically, the displacement could be arrived at by two main approaches, namely geotechnical approach and geodetic approach. Geotechnical approach uses the special devices such as strain gauges, piezometers, tiltmeters, extensometers and many others to obtain the required type of displacements. However, the geodetic approach uses the surveying positioning techniques to derive the displacement. Either geotechnical or geodetic approach, they can be employed to measure / monitor the displacement of the man-made structure (e.g. dam, high-rise building, bridge, tunnel, etc.) and natural features (e.g. slope and the areas encountering with landslide, subsidence, liquefaction, uneven settlement, mass movement, etc.).

The thesis focuses on the geodetic approach. The main difference of the geodetic approach is that it uses the surveying technique to provide the feedback of the response of the monitored object in term of position, which is, in turn, used to derive the displacement (magnitude and direction) as well as displacement speed (velocity). The derived displacement can be then described as deflection, settlement, drift and others. For this reason, displacement measurement is also comparable to deformation measurement.

Besides, in geodetic approach, there is also a number of positioning techniques that can be used to perform the displacement measurement, such as conventional terrestrial based method (by using theodolite or total station), global positioning system (GPS) and photogrametry (by using camera or scanner). However, GPS is the positioning technique to be looked into in this research.

Moreover, regardless to the positioning mode (absolute positioning or relative positioning), GPS positioning technique can be further divided into two different technique, namely, static positioning and kinematic positioning. Yet, the research focuses on the kinematic positioning with real-time solution or in short real-time kinematic (RTK) positioning technique.

Summing up all the comments abovementioned, in short, the main focus of the research scope is shown in the “reserve pyramid” in Figure 1.1.

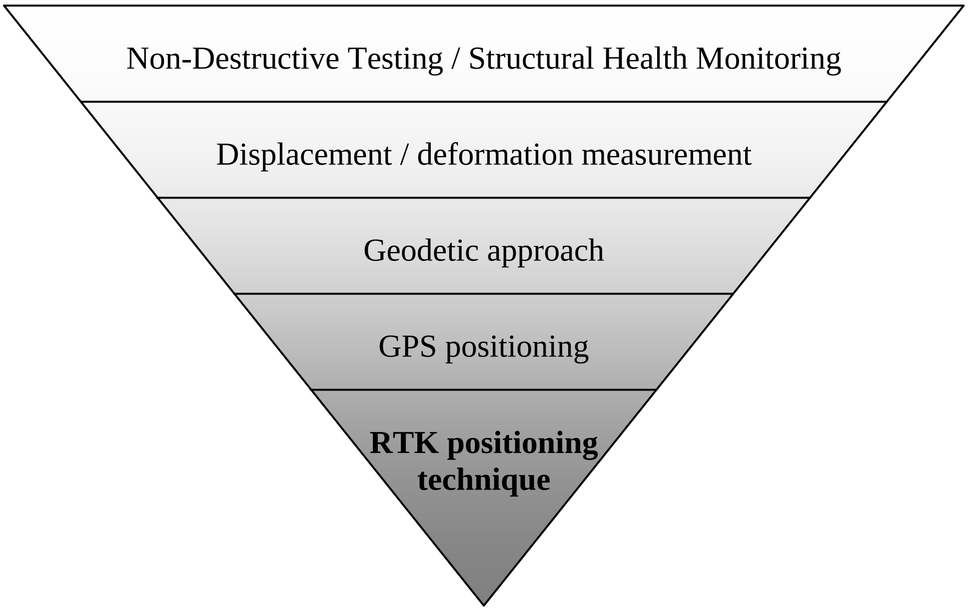

Figure 1.1: Main focus of the research scope.

Before continuing the discussion, some statements on the terms used in the thesis are advisable. Throughout the thesis, displacement and deformation are comparable. However, deformation measurement and deformation monitoring are not quite comparable. Deformation measurement is used to represent the quantitative measurement, whereas, deformation monitoring is used to represent the practice in the real scenario, inclusive of both deformation measurement and analysis.

1.2 Problem Statements

Back in the late of 1970s, the GPS technology was introduced when the first launch of the GPS satellite on February 22, 1978 (Leick, 2004). Since then, many industries have been benefited from the technology of GPS. Surveying industry has been no different. Researches have been (and are still) carried out and benefits have been (and are still) brought in. However, due to the expensive equipments (as compared to the conventional terrestrial surveying equipments), GPS technology is still fresh in Malaysian surveying industry. Only the education institutions and government departments have the regular practices. Furthermore, Malaysia, the country that has been gifted the advantageous geographical and geological location (e.g. free from earthquake and volcano), have no intensive practices in monitoring (structures as well as natural events). This also results the lack of proper reference or standard guideline for using GPS in deformation monitoring. Nevertheless, as it has been discussed in Section 1.1, there are, in truth, the needs of deformation monitoring in Malaysia.

Today RTK positioning technique is certainly one of the most valuable assets of GPS. Although many researches have suggest and proven the feasibility of using RTK positioning (examples are given in Section 2.5) in deformation monitoring, directly employing the manufacturers' RTK positioning solution (the output obtained from the receiver) in deformation monitoring is doubtful. In other words, the possible errors (e.g. multipath and cycle slips) and reference station reliability that deteriorate the quality of RTK positioning are the main concern.

Besides, the main essence of RTK positioning is its advantage to provide the direct measurement of relative displacement and real-time measurement (online and offline application). Nevertheless, until latest, there is still very lack off-the-shelf online RTK positioning application, while offline RTK positioning solution does not offer the real time (on the spot) deformation monitoring. Real time deformation detection plays the prominent role in guaranteeing public safety.

Furthermore, automated and continuous monitoring is also the latest and in demand monitoring. This is because automated and continuous monitoring greatly levels the efficiency of deformation monitoring, such as, saving the manpower, reducing human gross error and handling the round-the-clock monitoring. However, the smart and handy applications have to be self developed or customized.

A reliable RTK positioning technique for deformation monitoring and a computer-aided approach to perform the online, automated and continuous deformation monitoring are the concern of the thesis.

1.3 Research Objectives

Based on the problem statements discussed in the previous section, the research objectives are as follows.

(i) To investigate RTK positioning integrity monitoring and deformation detection method to improve the direct employment of manufacturer’s RTK positioning technique for deformation monitoring system.

(ii) To enhance the employment of RTK positioning technique in deformation monitoring, particularly in online, automated and continuous deformation monitoring by developing prototype software.

1.4 Research Contributions

Parallel to the research objectives, the research has two significances as follows.

(i) An additional method for RTK positioning integrity monitoring (inclusive of RTK output quality and reference station stability) and deformation detection is proposed.

(ii) A prototype deformation monitoring system for automated, online and continuous monitoring scheme is developed. The prototype can be reference for structure deformation and landslide study that concerns the public safety in Malaysia.

The main difference between the research and other glorious and famous researches is that the research looks into an additional method for manufacturers’ RTK positioning solution which concerns the RTK integrity monitoring and deformation detection so that it can be employed directly for online, automated and continuous deformation monitoring. Algorithm development for processing raw GPS data to obtain the RTK solution for deformation monitoring is not in the scope of the research, yet, it is recommended for future work.

1.5 Research Methodology

The process of the whole research is summarised as shown in the flow chart in Figure 1.2.

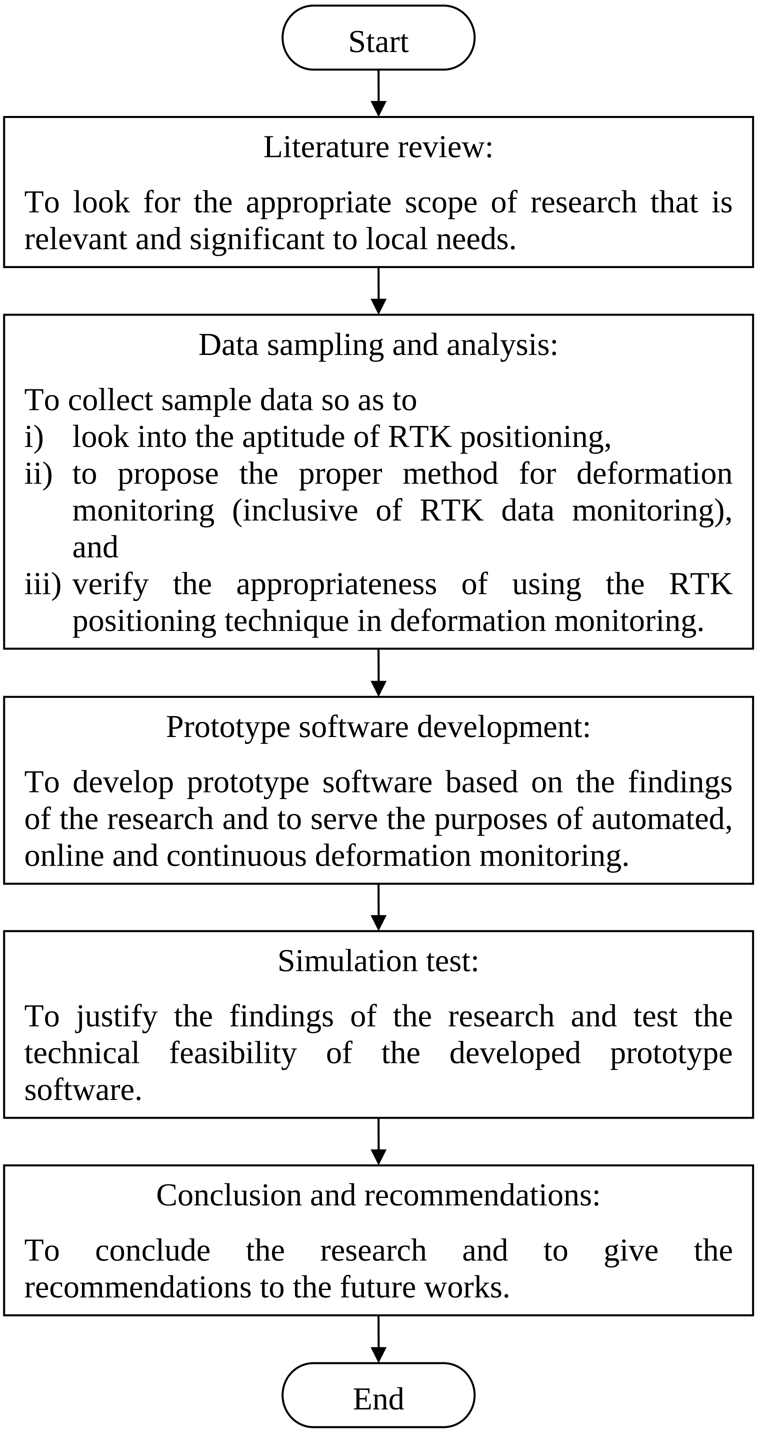

Figure 1.2: Research methodology.

1.6 Outline of the Thesis

The thesis consists of seven chapters and six appendixes.

Chapter 1 gives the introduction to the research by delivering the background of the research, problem statements, research objectives, research contributions, research methodology as well as structure of the thesis.

Chapter 2 peruses the development of deformation monitoring (global development of deformation monitoring, classification of deformation models and terminology, and classification of monitoring schemes) and the employment of GPS in deformation monitoring (scientific justification and technical feasibility, competency of RTK positioning in deformation monitoring, and state-of-the-art deformation monitoring system).

Chapter 3 discusses the fundamental of GPS positioning as well as RTK positioning technique. The chapter begins the discussion from the basic of satellite positioning until the scope of RTK positioning, that include GPS signal structure, GPS ranging, and GPS positioning mode, absolute positioning, relative positioning, and kinematic positioning.

Chapter 4 discusses the GPS accuracies, error and bias sources, and augmentation options so that they can be referenced in the following chapters.

Chapter 5 presents the results of sampled data, and proposes an additional method for RTK positioning integrity monitoring (error identification, outlier filtering and reference station stability checking) and deformation detection.

Chapter 6 describes the developed prototype software, Sparrow. The description includes the Sparrow briefing, software design, software structure and software functionalities. Besides, three tests to verify the applicability of Sparrow and validity of Normal Point (NP) are included.

Chapter 7 gives the concluding remarks of the research as well as the recommendations to the future works.

Appendix A attaches the Section 85_A from the Street, Drainage and Building Act 1974 (Act 133).

Appendix B attaches four examples of enhancements of data processing, algorithms or software.

Appendix C presents the results of sampled forty-eight-hour continuous RTKNet data.

Appendix D elucidates the National Marine Electronics Association (NMEA) 0183 Standard.

Appendix E discusses the conversion from geodetic coordinate system to the user-defined coordinate system used in the research.

Appendix F describes the field procedure of using Sparrow as well as process and result of the tests for the developed prototype software.