STRUCTURAL MONITORING DETECTION USING GLOBAL POSITIONING SYSTEM

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To my beloved family

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ABSTRACT

Many man-made structures such as high rise building undergo various forms of deformation and it requires mitigation measures to understand the causes and mechanism of deformation. Global Positioning System (GPS) is utilised for positioning in three dimensional and has been used to monitor deformation magnitude of structure. The GPS Real Time Kinematic (GPS RTK) and Static are part of GPS positioning methods. GPS static in high accuracy, able to observe in all weather conditions and no requirement for inter-visibility, with aids of internetworking services can provide the near real time result in observation. The limitation on GPS RTK in radio link communication such as the canopy obstruction between base and rover stations will interrupt communication. The objective of study is to investigate the implementation of structural monitoring system using GPS for deformation analysis on structure in near real time. Data transmission of GPS Static between monitoring stations and central processing unit is using internetworking services. The significant role of GPS static survey in identification of structural stability has been studied and explored, with the evaluation focuses on session length in structural monitoring and network configuration. The developed system consists of planning and preparation of GPS survey, GPS baseline reduction, network adjustment and deformation processing as incorporated in GPS Static Adjustment and Deformation Detection (GPS STAAD). The accuracy and reliability of GPS STAAD have been verified with other resources, namely GPSAD2000 and NETGPS and the result shown all the points in the network are stable. This result has been tested in simulation test and shown that a deformation movement of up to 20mm level has be detected by the program. In conclusion, feasibility of applying the GPS Static method in structure monitoring, as well as implementation of structural monitoring system is successfully studied.

ABSTRAK

Banyak struktur buatan manusia seperti bangunan tinggi mengalami pelbagai bentuk deformasi dan memerlukan langkah-langkah mitigasi untuk memahami punca dan mekanisma deformasi. Sistem Penentududukan Sejagat (GPS) digunakan untuk penentududukan dalam tiga dimensi dan telah digunakan untuk memantau magnitud deformasi terhadap struktur. GPS kinematik masa nyata (GPS RTK) dan Statik adalah kaedah penentududukan GPS. Statik GPS berketepatan tinggi, boleh dicerap dalam semua keadaan cuaca dan tiada keperluan terhadap kebolehlihatan, dengan bantuan perkhidmatan antara rangkaian boleh memberikan hasil menghampiri masa nyata dalam cerapan. Pengehadan GPS RTK dalam sambungan komunikasi radio seperti halangan kanopi antara stesen rujukan dan penerima akan mengganggu komunikasi. Objektif kajian adalah untuk mengkaji pelaksanaan sistem pemantauan struktur yang menggunakan GPS untuk analisis deformasi struktur dalam menghampiri masa nyata. Penghantaran data statik GPS di antara stesen penerima ke unit pemprosesan pusat adalah dengan menggunakan perkhidmatan antara rangkaian. Peranan penting statik GPS dalam pengenalan kestabilan struktur juga telah dikaji dan diteroka dengan, penilaian memberi tumpuan kepada tempoh sesi dalam pemantauan struktur dan konfigurasi jaringan. Sistem yang telah dibangunkan ini terdiri daripada perancangan dan persediaan untuk ukur GPS, pengurangan garis dasar GPS, pelarasan jaringan dan pemprosesan deformasi seperti yang digabungkan dalam sistem GPS pelarasan statik dan pengesanan deformasi (GPS STAAD). Ketepatan dan kebolehpercayaan GPS STAAD telah disahkan dengan sumber lain, iaitu GPSAD2000 dan NETGPS dengan keputusannya menunjukkan semua titik dalam jaringan adalah stabil. Keputusan ini telah disahkan dengan ujian simulasi dan menunjukkan pergerakan deformasi sehingga tahap 20mm telah dikesan oleh program. Kesimpulannya, kebolehlaksanaan kaedah statik GPS dalam pemantauan struktur dan pelaksanaan sistem pemantauan struktur berjaya dikaji.

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LIST OF ABBREVIATIONS

GNSS	-	Global Navigation Satellite System
GPS	-	Global Positioning System
RTK	-	Real Time Kinematic
IT	-	Information technology
NAVSTAR	-	NAVigation System using Time and Ranging
DoD	-	Department of Defence
MCS	-	Master Control Station
IGS	-	International GPS Service
UERE	-	User Equivalent Range Error
TEC	-	Total Electron Content
km	-	Kilometer
SA	-	Selective Availability
AS	-	Anti-spoofing
PPP	-	Precise Point Positioning
OTF	-	On The Fly
CAD	-	Computer Aided Design
DGPS	-	Differential Global Positioning System
RTCM	-	Radio Technical Commission for Maritime Service
NRTK	-	Network Real Time Kinematics
GLONASS	-	GLObal NAvigation Satellite System
SAR	-	Synthetic Aperture Radar
PPK	-	Post Processing Kinematics

LGO	-	Leica Geo-Office
PTDL	-	Precise Time Data Logger
WLAN	-	Wireless Local Area Network
IWST	-	Iteratively Weighted Similarity Transformation
ConDAS	-	Continuous Deformation Analysis System
CORS	-	Continuous Operating Reference Station
LAN	-	Local Area Network
TCP	-	Transmission Control Protocol
IP	-	Internet Protocol
NGS	-	National Geodetic Survey
GPS STAAD	-	GPS Static Adjustment and Deformation Detection
GOCA	-	GPS Based Online Control and Alarm System
KINDEF	-	Kinematic Deformation Analysis Program
RT-MODS	-	Real Time Monitoring of Dynamic System
DIMONS	-	Displacement Monitoring System
RTD	-	Real Time Dynamics
FTP	-	File Transfer Protocol
RINEX	-	Receiver Independent Exchange Format
WGS84	-	World Geodetic System 1984
PKPUP	-	*Pekeliling Ketua Pengarah Ukur Dan Pemetaan*
DSMM	-	Department of Survey and Mapping Malaysia
EDM	-	Electronic Distance Measurement
mm	-	Millimetre
RMS	-	Root Mean Square
KKTS	-	Kota Kinabalu Times Square
TBC	-	Trimble Business Center
TGO	-	Trimble Geomatics Office

GPSAD2000	-	GPS Baseline Adjustment and Deformation 2000
SMC	-	Sabah Medical Centre
ARP	-	Antenna Reference Point

CHAPTER 1

INTRODUCTION

1.1 Introduction

The Global Positioning System (GPS) is a space based Global Navigation Satellite System (GNSS), and consists of a constellation of 24 satellites which are freely accessible by anyone with a GPS receiver on hand. It provides location of the users at anywhere on the earth where is an unobstructed line of sight to four or more GPS satellites at the space, it meant it offers a reliable and efficient method for three-dimensional survey: X, Y and Z. Nowadays, GPS has been fully deployed and useful tool for commercial uses, scientific uses, tracking, and surveillance. Beside, GPS is also being used in car navigation, topographical and cadastral survey in land surveying, deformation studies for stability of structure, and vessel navigation in hydrographical survey because GPS provide real time or/and post processing result of positioning. More researches have been carried out in order to improve and enhance the precision and accuracy of GPS. With this contribution and GPS to be played an important role in high precision geodetic surveying, such as deformation survey/monitoring to monitor the stability and safety of deformable bodies or structures.

For the last few years, the GPS deformation monitoring applications have shown that GPS is a surveying tool which is capable to monitor sub-centimetre deformation. Ogaja *et al.* (2001) mentioned that GPS technology can measure directly the position coordinates and relative displacements can be measured at rates of 10Hz and higher. This provides a great opportunity to monitor, in real time, the displacement or deflection, behaviour of engineering structures under different loading conditions, through automated change detection' and alarm notification procedures. According to Hudnut and Behr (1998), monitoring the integrity of engineered structures demands very high precision displacement measurements from a robust system, as close as possible to real-time. In addition to dams, other types of engineered structures such as freeway overpasses, bridges, and high-rise buildings can feasibly be monitored using continuous GPS. Continuous data recording from the GPS satellites, using ground-based receivers and robust telemetry, can be used for monitoring the health of engineered structures, and can thereby be useful for the public safety aspects of civil, structural, and earthquake engineering.

Deformation is defined as a change of shape or size of an object due to external force in tensile, compressive or torsion. The deformation may cause the damage to structures and failure of structure, by then cause the loss of people life and human property. Therefore, it is important that deformation survey to be taken in place to determine the stability of position of object points on the monitored structure, wherever one dimensional, (1D) (vertical), two dimensional (2D) (horizontal position) and three dimensional (3D) (horizontal and vertical) were still in fine condition. Previously and normally conventional surveying instruments, e.g. total station and automatic level has been used to determine the horizontal and/or vertical positions of structure. A network of reference stations located in stable areas nearby the project site and away from monitored structure is established. The elements of distance, angle, and height difference measurements are made to object points on the monitored structure using survey equipment. The working methodology and procedures consist of moving equipment from point-to-point and observing, recording, and checking field data on-site has been defined, planned, and executed accordingly. Final coordinates are obtained from a least squares adjustment on the survey observations data by using the fixed coordinates of the reference network. Position differences are observed over time (normally epoch by epoch) at each object point. These define a specific displacement field valid for the time span between two surveys result.

The accuracy requirements for performing deformation surveys shall be decided and determined by the users. The accuracy criteria must be defined relative to the particular structure's requirements, not the capabilities of a survey instrument or system. The common accuracy requirement required in deformation survey is shown in Table 1.1. These represent the accuracies of either absolute or relative movement on target points of monitored structure that should be attained from survey observations made from external reference points. The accuracy by which the external reference network is established and periodically monitored for stability should fulfill these accuracies. All the survey equipment, e.g. total stations, digital levels, GPS device etc. are easily and capable to achieve the said accuracies as shown in table.

Table 1.1 : Accuracy Requirements for Structure Target Points (95% RMS) - (USACE, 2002)

Concrete Structures: Dam, Outlet Works, Locks, Intake Structures.	
Long-Term Movement	± 5-10 mm
Relative Short-Term Deflections	
Crack/Joint Movements/Monolith Alignment	± 0.2mm
Vertical Stability/Settlement	± 2mm
Embankment Structures: Earth-Rock fill Dams, Levees.	
Slope/Crest Stability	± 20-30mm
Crest Alignment	± 20-30mm
Settlement Measurement	±10mm
Control Structures: Spillways, Stilling Basins, Approach/Outlet Channels, Reservoirs.	
Scour/Erosion/Silting	± 0.2 to 0.5 foot

In the market today, there is several deformation monitoring systems available as follows:-

(i) RT-MODS – Real Time Monitoring of Dynamic System (2000), developed at Istanbul Technical University by Ince and Sahin (2000).

(ii) Grazia (2002), developed at Graz University of Technology, Gassner *et al.* (2002)

(iii) GOCA – GPS Based online control and alarm system (2000), developed at Karlsruhe University of Applied Sciences in cooperate with the EuroNav, Kalber *et al.* (2000)

(iv) Trimble Total Control and Motion Tracker Module- developed and published by Trimble (2014).

The deformation monitoring system listed above can be divided into different categories according to the way of using or/and processing the observation data. The first category is use the real time result calculated and obtained in the GPS receiver, and normally defined it as deformation monitoring with Global Positioning System Real Time Kinematic (RTK-GPS). RT-MODS are one of the typical software in this category of monitoring system. GOCA is also applying and use same principle above by using RTK observation data, instead of taking the coordinates directly from the receiver, it performs adjustment processing to all the observation data and the outliers can be detected and filtered to achieve good result in deformation monitoring.

The second category of deformation monitoring system is categorized by the use of the observed raw data. The observation data from the GPS receivers are downloaded, stored and sent to a linking central computer where the calculations are performed to obtain the deformation monitoring result. Grazia is the software that follows this approach with processing method by double differenced observation. Meanwhile, Trimble Total Control and Motion Tracker from Trimble also belongs in this category which it performs further steps with deformation analyses using different approach, and alarm system activation will be turned on when failure of structure is detected.

Most of the studies focused and developed monitoring program based on GPS RTK survey positioning method in order to provide near real time result in structure monitoring, for instance RT-MODS, GOCA etc. This study evaluated the observation of GPS Static is not just stand alone system in point positioning method.

Internetworking services ensure all monitoring points are connected and GPS Static data can be transferred between all stations to master processing centre in near real time. Data observation of GPS Static is used in computation and analysis for structural deformation monitoring. The result of GPS data analysis is subjected to program developed to process and analysis the collected data thru internetworking in order to determine the stability of structure. As a case study, this assessment was implemented in a high rise to utilize structural monitoring system using GPS.

1.2 Problem Statements

The need for structural monitoring of large engineering structures often arises from concerns associated with environmental protection, property damage and public safety in order to avoid loss of life, large financial expenditures and to minimize environmental damage. The GPS recently has emerged as a survey tool for structural monitoring applications. Results analysis for test on accuracy of RTK-GPS baseline from author's previous study (Shu, 2005) found that maintaining the line of sight is important and necessary for radio link communication between base and rover in RTK-GPS survey in order to provide continuous data for real time deformation survey. The study proven that the radio link communication was interrupted in canopy area where it acted as an obstruction between base and rover during observations. There are many constraints of RTK-GPS, including point to point communication link, lower accuracy result in surveying compare to GPS Static, also no further and additional post processing is required in RTK-GPS. With the abovementioned and discovered limitation, the GPS Static survey in good result of higher accuracy and precision, and it incorporated with aids of internetworking services to ensure all the points are connected and data transference to master processing centre for processing and analysis to provide the near instantaneous result in observation. Subsequently, GPS Static incorporated with internetworking services is recommended and been studied in development of structural monitoring system.

GPS Static survey offer several advantages compared to conventional terrestrial methods. Inter-visibility between station and station is no longer strictly necessary and required, and it allows greater flexibility in the selection of station locations. Measurements can be taken during night or day and under varying weather conditions where terrestrial geodetic method unable to fulfil this requirement, especially observation at night. A structural monitoring system using GPS is required to provide continuous updates result in near real time where the structure is undergoing repairs or maintenance. Communications links must be built into the system to allow GPS static data transfer between GPS receivers located at monitoring points and central processing computer. The research studied and explored the significant role of GPS Static survey in identification of structural stability in development of structural monitoring system. The research studied the quantification of 3D GPS Static coordinate into deformation magnitude and direction in order to determine significant deformation or vice versa. Prior to the development of structural monitoring system using GPS, further research in detail is required to develop proper data observation and processing which can effectively obtain a good result in structural monitoring requirement. The appropriate procedures of GPS Static observation and processing intended for structural monitoring system also being investigates in the study.

Many of structure monitoring system may be effectively used in the practical applications, some refinements and further developments are possible. An important further development is to allow the system to be used, customised and based on the available property. An interesting area of this further activity is a structure monitoring system can be in a single platform and combination of different type of GNSS device in measurement and processing. This in turn will bring any desirable benefits from the system, even at data observation, data achieve, data import, data processing: baseline reduction & least square adjustment and deformation studies and analysis. Most of the structure monitoring study is focuses on direct coordinate comparison from epoch to epoch, especially at commercial software in industry practice. The research studied on the importance of deformation study and analysis on program development in structural monitoring system where it will obtain more realistic and reliable information about displacement which are tested statically in order to reduce uncertainty in the typical coordinate comparison analysis. The structural monitoring system using GPS will decode the raw binary GPS data, process the data, generate output solution and display the result in near real time. The result from the system can then be used for determination of structural stability. Successfully implemented, the research will yield a unique structural monitoring system.

Research is on-going by equipment manufacturer to introduce new technology to incorporate the integration of additional GNSS observations for instance Global Navigation Satellite System (GLONASS) from Russian where it offers higher precision solution and potentially more continuous updates compare to by using stand-alone GPS. Despite offering increased satellite visibility, however, there is no assurance that satellite geometry will provide the required level of accuracy and precision in certain environments. The study investigates the beneficial of integration of additional GLONASS in data processing with GPS to achieve effective and good result in structural monitoring.

The study focuses on the development and implementation of structural monitoring system using GPS. It is developed under object orientated MATLAB software where it allows the system to be used and customisation for further development is possible. The high accuracy of GPS Static data in structural monitoring system from all the monitoring points can be connected through internetworking services and transferred to master processing centre for processing and analysis purpose. The processing effectively produce a good result in computation based on baseline reduction, least square adjustment and statistical test of deformation analysis against to direct coordinate comparison from epoch to epoch in industry practise. It also overcomes the limitation of point to point communication in RTK-GPS.

1.3 Research Objectives

The aim of this study is to investigate and determine the utilization of GPS Static whether in practice and can be used in deformation monitoring of structures. More specifically, the following main objectives are presented to achieve it: -

(i) To evaluate the effectiveness of processing methods used in structural monitoring system. The procedure focuses on session length in structural monitoring, network configuration and effect of employment of GLONASS data for solution improvement.

(ii) To investigate the implementation of structural monitoring system using Global Positioning System (GPS) in near real time for deformation analysis on structure.

(iii) To determine the deformation magnitude on case study: Sabah State Administrative Centre by utilizing structural monitoring system using GPS.

1.4 Research Scopes

The study concentrates on the development of structural monitoring system, work methodology and technique being studied for possible implementation of GPS application for structural monitoring purpose. The research scopes of this study are as follows:-

(i) Acquisition of data for structure monitoring system based on GPS Static survey method. Communications and internetworking between stations for data transferring from remote stations to master station in near real time for processing.

(ii) Structure monitoring system based on the processing and analysis of the GPS baseline reduction, GPS network adjustment and also deformation detection. Criteria and processing requirement was elaborated accordingly.

(iii) Stability of structural to be studied thru deformation monitoring with a program developed and named as GPS STAAD (Global Positioning System Static Adjustment And Deformation). It process and analyse on the observed and collected data. The correctness and workable of the program in the processing and result analysis to be examinated with comparison with other program and simulation test.

(iv) The ability and capability of instrument, effect of session length in structural monitoring, network configuration, effect of employment of GLONASS data for solution improvement of structural monitoring system using GPS.

(v) The structural monitoring system using GPS result on case study: Sabah State Administrative Centre.

1.5 Significance of Study

The significances of this study are summarized in follows:

(i) The GPS Static survey technique is presented for deformation monitoring by providing good accuracy in surveying. The Static survey data can be up to millimeter accuracy is utilized for deformation analyses in determining stabilize of structure in a small scale area, for instance building structure.

(ii) A structural monitoring system in near real time based on GPS is developed. The observed GPS data is sent through communication system with internetworking in near real time for processing at master station. Baseline reduction and least square adjustment to be carried out on the data. Further result analysis of statistical test, such as congruency test, single point test etc. for deformation studies to be performed if required. The structure monitoring system in this study will provide information of position changes, in horizontally or vertically.

(iii) Structural monitoring using GPS with respect to error mitigation. The error mitigation is subject to the work and processing strategy of the technique. A good and suitable strategy should be taken in place to obtain a true deformation without error and bias in deformation monitoring. This study customised an appropriate work and processing strategy for deformation monitoring which can achieve monitoring result effectively. The benefit from the approach is to verify the reliability of the GPS survey technique in deformation monitoring.

1.6 General Methodology

In order to accomplish the study successfully, general methodology is providing as concise as possible as shown in Figure 1.1. The general methodology is divided into a few stages: literature review, development of structure monitoring system and work methodology and data processing as presented in respective chapter to achieve the objectives.

Literature review focused on concepts of GPS and deformation surveying or structural monitoring. The current GPS applications in deformation monitoring have been reviewed to understand the error sources involved in, type of survey positioning method and its mechanism etc. The type of network monitoring, technique used for deformation monitoring, type of baseline processing and adjustment method, basic concepts and methods of deformation analysis have been studied to understand and know the stability and effectiveness of selected method to be used for deformation monitoring. In order to develop structure monitoring system, the observation data have been recorded and transmitted from the remote control station (observation station), and received by the master control station (for processing) in near real time by using internetworking and communication system. In view of this, internetworking function is play a very important role to ensure the data acquisition process able to be in order and implemented. MATLAB software with object orientation features has been selected in development of structural monitoring system. The software has been widely used in all areas of applied mathematics in the research, education and industry. The workflow of structural monitoring system should be formed out. The type of GPS instruments to be used and its configuration, software to be implemented, connection between the stations, surveying, processing, adjustment and deformation analysis method should be studied and ensure the workable of system. The Trimble GPS instruments have been choose in this study and all the explanations of GPS device configuration is referred to Trimble as well.

Development of structure monitoring system is the main core of study. The aspects of data observation, data archive, data import in communication, and data processing and deformation detection are studied. The software architecture is reviewed. The system is developed with aids of MATLAB program and consists of networking, baseline processing, and network adjustment and deformation detection. The program will read GPS Static observation data from GPS receiver, and then data will be imported to a master processing centre for performing data processing: baseline reduction, least square adjustment and then structural monitoring analyses. The developed GPS monitoring system has been tested with data and simulation test from author's previous study (Shu, 2005). The purpose of these testing is to evaluate and verify the system's effectiveness and correctness. The developed system can be used in hazardous conditions, where the structure is undergoing repairs. Configuring, testing, and commissioning of system is performs to implement and run the entire system and provide a warm to the users, if any movement exceeds a safety threshold.

Work methodology and data processing is reviewed in the study. The work methodology consist of planning and preparation of GPS project by identifying positioning requirement, selection of positioning technique, selection of receiver type, GPS calibration, validation, reconnaissance, survey design, work preparations and field operation procedures. As mentioned earlier, the Trimble survey equipment has been selected to be used in this study. Testing of GPS device and positioning method is carried out to ensure functionary of the equipment, as well as positioning technique is fulfil the accuracy requirement. Survey duration in structure monitors and type of survey network in radial or triangulation also been studied. The procedures and processing criteria of baseline reduction, least square adjustment and deformation detection have been studied and tested to determine the workflow and requirement of structural monitoring system. The work methodology and structure monitoring system have been studied and implemented in a case study.

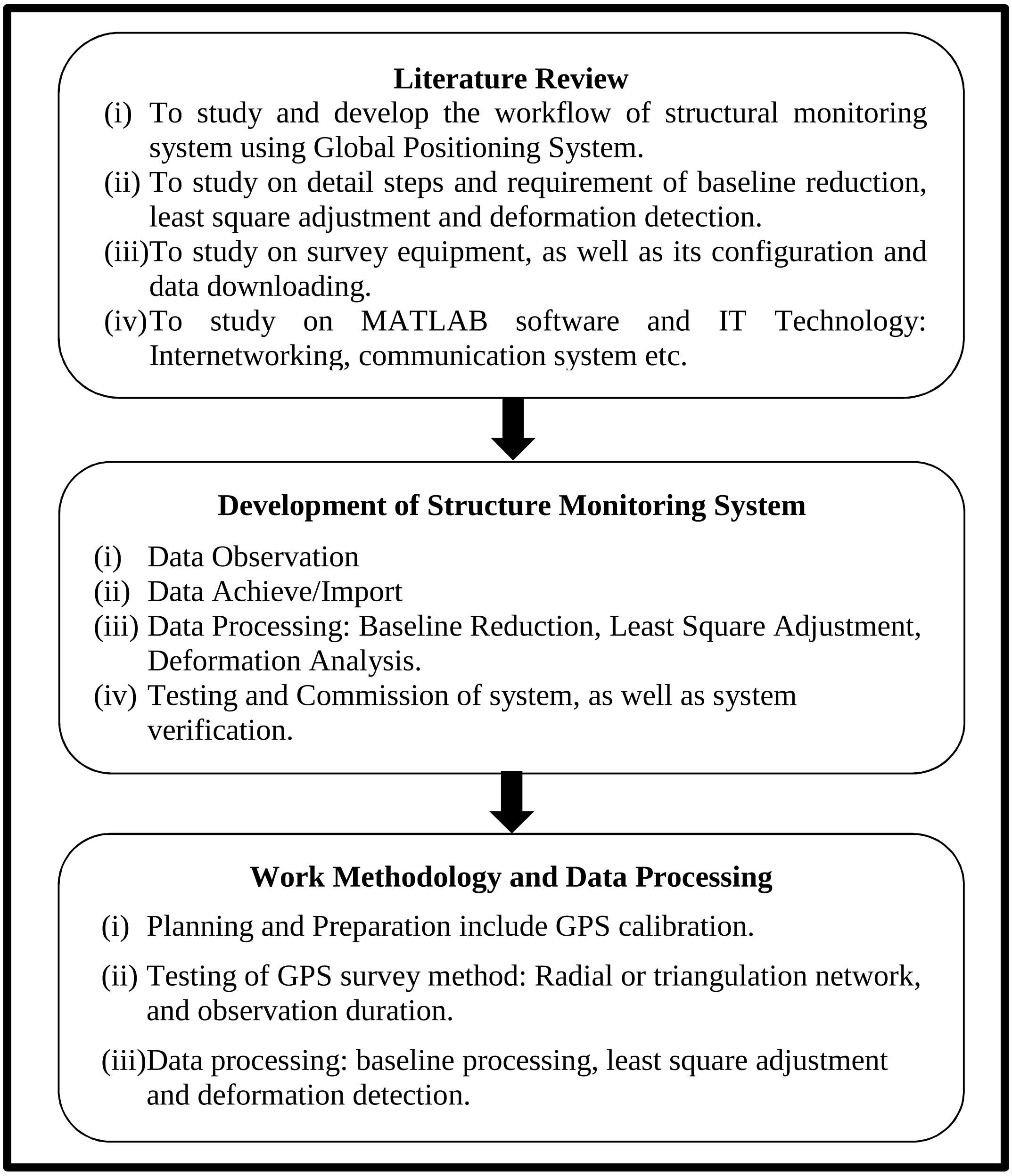

Figure 1.1: General Methodology Flow

1.7 Outline of the Thesis

This thesis consists of six chapters and organised as follows.

Chapter 1 contains the introduction of study, problem statement, research objectives, research scopes, significance of study and general methodology. The outlines of the thesis are presented also.

Chapter 2 is entirely focused on literature review on concepts of GNSS and GPS, GPS application in structural monitoring and the understanding of the GPS instrumentation. The workflow of structural monitoring system has been highlighted. The type of network monitoring, technique used for deformation monitoring, baseline processing and adjustment method, concept and method of deformation analysis has been studied.

Chapter 3 is the main core of thesis. Data observation, data archive, data import in communication, and data processing and deformation detection have been studied. The software architecture is also outlined

Chapter 4 presented work methodology of the study and case study. The work methodology consist of planning and preparation of GPS, selection of positioning technique, selection of receiver type, GPS calibration, validation, reconnaissance, survey design, work preparations, field operation procedures, procedures and processing criteria of baseline reduction, least square adjustment and deformation detection. The workflow and requirement of structural monitoring system has been studied, also implementation in a case study.

Chapter 5 presents the results and analysis of the studies. Analyses in this study include the reliability of the survey equipment thru GPS calibration. Effectiveness of GPS positioning network in structure monitoring and survey duration in structure monitoring have been analysed. The processing method includes baseline reduction, least square adjustment and deformation detection have been analysed as well. The developed program used in performing structural monitoring and analysing the GPS observation data between stations remotely in determining the stability of the structures in the case study. It also has been tested with other programs and simulation test to confirm correctness of the developed program.

Chapter 6 presents conclusions of the study and discusses the suggestions and recommendations to further improve study, future research and potential development.

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