Annotated Confirmation Report

Mobile Laser Scanning for Underground Railway Systems

The Hong Kong Polytechnic University

MOBILE LASER SCANNING FOR UNDERGROUND RAILWAY SYSTEMS

Include the following on the title page:

i. name of the supervisor

ii. date of submission

iii. your department

Include an abstract

Table of Contents

Include a list of abbreviations.

Special Note:

The page numbers may not exactly match those in the report due to the annotations.

Table of Figures

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✓ Section 1 provides a clear explanation of the background to the topic. Then outlines the major problem and explains how the problem could be overcome. Next it outlines how this project will address the issue and finally gives a clear outline of the rest of the report.

1. Modern Rail Transport

Include the word "Introduction" in the title of section 1.

Railways are essential component of the public transportation system in many countries. In modern society, rapid transit systems or metros are significantly important to daily necessity in urban cities. Complex railway networks are designed to support a great demand of passenger transport with high level of safety, efficiency, service stability and reliability.

✓ Describes importance of field and so establishes importance of research

1.1. Importance of Underground Railway

Rail transport in urban areas, especially underground railways, are usually complex networks to serve for the large demands of passengers over large areas. It acts as an alternative transportation system operated inside tunnels, which is stable, reliable, safe and is out of traffic congestion. Consequently, tunnel structural health and operation safety are the essential elements that safety requirements are accomplished by various monitoring works conducted in real-time or periodically for rail track and tunnel sections.

✓ Explains key concepts

In Hong Kong, the ***Mass Transit Railway*** (MTR) is a heavily patronized railway network, which carries more than 4 million passengers per day in average (HKSARG, 2013). Every minor delay might cause serious influence. In order to minimize the risks, major control systems are designed with fail-safe and proved to be faultless in signaling structure ("Transport Canada," 2007). While the safety and performance requirements are extremely strict, however, service delays and accidents still occur frequently, which is not limited to inconvenience to passengers, but also possible to cause financial and social impacts.

✓ Narrows scope of study to Hong Kong

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1.2. Instances of Service Disruption

In modern railway systems, the railway operation is supervised and regulated through well-developed train control and signaling systems. However, unexpected situations are unavoidable and minor accidents still frequently occur.

Avoid overusing the structure "In XX, …" at the start of paragraphs better a strong subject, i.e. "The operation of modern railway systems is…".

For instance, the service of MTR Island Line had been suspended during the morning rush hours on 03rd October, 2012 (Ngo, 2012). The service suspension is caused by a ventilation duct cover which came loose from tunnel wall and blocked the tunnel. Large crowds built up on station platforms, and MTR Corporation had to arrange free shuttle buses for stranded passengers. Normal service was recovered after 2 hours.

Place examples in the same paragraph as the point they are referring to.

Another accident happened on 23rd July, 2012. Hundreds of commuters were stranded inside trains and MTR stations after service was suspended due to broken cables and fallen trees, caused by Typhoon Vicente (Cheung and Lee, 2012). Many residents were forced to sleep in train stations overnight, while others had to brave the fierce winds and rain to reach home.

In addition to minor service disturbances, serious accidents may also be possible for advanced railway systems. For example in China, a rear-end collision occurred at the Shanghai Metro Line 10 on 27th September, 2011. It is caused by a mistake during manual train operation after a signal failure in Xintaindi Station (Wade, 2011). Over 200 passengers were injured and fortunately no fatalities have been reported.

✓ Links well to previous paragraph, e.g. "In addition to minor…,"

The most serious derailment in the light-rail network history of Hong Kong happened in Yuen Long on 17th May, 2013 (Ngo, 2013), which was caused by a software bug in the main

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computer of the train control system at a station. 77 passengers were sent to hospitals and the suspension lasted for more than eight hours. The MTR Corporation could be fined with maximum amount of HK$15 million for such accident.

The social and economic impact caused by railway service disruption is difficult to estimate. For the service provider, spending for alternative traffic arrangement, cost of repairs, penalty, loss of reputation and extra promotion are possible consequences. For the customer aspect, loss of time and money is critical especially during rush hours. Considerable amount of lives are under risk, while serious accidents could cause huge social impact.

> Avoid the "For…," construction. Use a strong subject, i.e. "Service providers lose because…".

It is not unusual that railway accidents occur frequently in railway systems worldwide. Although the modern railway systems are developed with highly automated functions for achieving operation reliability, accidents cannot be eliminated for unexpected situations.

1.3. Deficiencies of Railway Systems

For highly automated railway systems, trains are supervised by train operators or ***Operation Control Centre*** (OCC), while the basic train operations, such as acceleration and braking, are controlled and regulated by ***Automatic Train Protection*** (ATP), ***Automatic Train Control*** (ATC) or higher levels of automated control systems. In general conditions, the operational efficiencies such as energy consumption, traction and braking, speed regulation, and headway maintenance are significantly enhanced by system automation (Dominguez et al., 2011). Nevertheless, unexpected conditions such as obstacles or undetected malfunctions may cause unpredictable consequences or even disasters.

> ✓ Introduces key terminology with abbreviations used first time they are introduced
>
> Do not use bolded font for key terms.

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In underground railways, the illumination in railway tunnels is poor, such that the sighting condition is degraded. If there is an obstacle on track, it is difficult to detect before accidents occur. It would be time consuming to identify, locate and fix the problem. The consequence can be simply service suspension for minutes or hours, or can be as serious as collision or derailment causing injuries or lives.

Do not use "would" unless the situation is unreal. Better to state, "it is time consuming…"

Service disruption can be caused by malfunctions of signaling system, such that manual train operation may be required for maintaining railway service by degraded operation mode. Alternative visualization and train detection is critical for safety enforcement.

✓ Highlights importance of topic and therefore the importance of this research paper

1.4. Supplements for Railway Operation

It cannot be denied that a train-borne measurement system for monitoring trackside conditions, obstacle detection, and supporting train-borne operation would be significantly useful to overcome the deficiencies of general railway systems.

Avoid absolute statements, e.g. "It cannot be denied". Use "A train-borne …is essential to overcome…

Present simple tense "is" is a better option than "would be", which is more suited for unreal situations.

Research has been conducted for utilizing remote sensing techniques to implement the obstacle detection. For passive remote sensing, 3-dimensional spatial data can be extracted from stereo-images through photogrammetric method, which has been widely studied for visual-based object detection (Oh et al., 2008; Uribe et al., 2012). However, the performance of passive method is highly dependent on the illumination, which is probably poor in dark environment such as the railway tunnels. Consequently, active methods such as ***Light Detection***

✓ Uses present perfect to describe recent research, e.g. "has been conducted", "has been widely studied"

✓ Highlights limitations of current approaches.

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And Ranging (LiDAR), or ***Radio Detection And Ranging*** (Radar) would be better alternatives. They are independent of illumination conditions and more suitable for measurement or obstacle detection in railway tunnels (Kruse et al., 2002; Passarella et al., 2011).

Laser scanning is an advanced measurement system developed with LiDAR technology, which can acquire 3-dimensional relative position of points in high density and maps the environment through point cloud. ***Mobile Laser Scanning*** (MLS) is an integrated dynamic solution for laser scanning, which is a potential solution to be a train-borne measurement system for supporting the railway operation.

✓ Explains how limitations of the current system can be improved

1.5. MLS for Underground Railways

MLS has already been increasingly introduced to railway environment for rail track and infrastructure survey, clearance measurement, or railway tunnel mapping etc. However, the applications usually rely on ***Inertial Navigation System*** (INS) with ***Global Navigation Satellite System*** (GNSS) for geo-reference solution. Performance is degraded when the systems are operated in GNSS-outage environment, which mainly depends on the quality of ***Inertial Measurement Unit*** (IMU). Although the MLS configuration is simplified and decomposed into subsystems for some railway tunnel applications, the functions of decomposed MLS are restricted by system design.

✓ Discusses solution in more detail highlighting weaknesses of their current use

In Hong Kong, railway network has a total length over 200 km (HKSARG, 2013), while there are more than 90 km of railway sections are tunnels (CEDD, 2013). For underground railway sections, a

Put the main point first. i.e. GNSS is highly suitable for Hong Kong. The Hong Kong railway network…"

✓ Explains why system would be suitable in Hong Kong

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train may rarely, or even never have a sky view. Consequently, having a system that is independent of GNSS would be an advantage.

In order to realize an effective and efficient MLS system for use in underground railway environment, several fundamental problems need to be solved:

✓ Lists current problems in numbered point form

1. Operation under GNSS-free environment;
2. Maintenance of navigation errors;
3. Effective system initialization and calibration inside tunnels.

After solving the problems, MLS technique can be better integrated with railway system towards an ***Underground Railway Laser Scanning*** (URLS) solution. The URLS solution can serve for active train-borne measurement and even self-localization in real-time, which opens up various directions of possible development, such as:

1. Real-time or near real-time monitoring of all underground infrastructure;
2. Train-borne hazard detection;
3. Alternative train localization;
4. Augmentation of train control automation.

✓ Gives specific details of advantages of overcoming problems

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1.6. Research Objectives for URLS

General MLS systems greatly rely on the navigation solution of integrated INS/GNSS and are weak in maintaining consistent performance with degraded navigation during GNSS-outage. In order to develop the MLS into URLS, GNSS-free solution is essential. At this stage, finite research has been conducted for enhancing the performance of MLS without GNSS, but it is still far from a complete solution.

> ✓States project aims in unique subsection
> ✓States clearly "gap" in current knowledge, e.g. "still far from a complete solution"
> ✓Explains how research will address the research gap
> ✓Gives specific ways research gap will be filled in separate subsections, i.e. "1.6.1 GNSS Replacement"

This research aims at contributing to the development of URLS by solving the navigation problems in terms of GNSS replacement. Alternatives for decoupling the GNSS positioning from MLS technique will be established towards a complete navigation solution for URLS.

1.6.1. GNSS Replacement

The integrated INS/GNSS solution has been established for long time to recover the deficiency of inertial navigation, such that the MLS technique was developed under a constrained navigation solution. The primary research objective is to identify and assess GNSS-free solutions by integrating the MLS into railway system, which aims at minimizing additional instruments and control surveys. Thus the availability of solution can be maximized.

> Avoid vague statements, e.g. "a long time". State "in the last two decades".

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1.6.2. Optimization for Underground Railways

Secondly, the Mobile Laser Scanning solution has to be optimized towards the Underground Railway Laser Scanning solution. The tunnel environment is more challenging for implementing the MLS than outdoor environment. Assessment of system design and processing algorithm is significantly important to overcome the problems of the object distance, availability of feature, train speed and motion, or necessity of instrumental calibration etc.

Avoid using "etc." End a list with "and a number of other related problems".

1.6.3. Exploitation for MLS in Railway Systems

The third objective is to exploit the complete integration of MLS technique to underground railway systems towards continuous operation. The integrated URLS can provide a more comprehensive solution for mapping and updating the rail track, wayside equipment, overhead cables and railway tunnel accurately. There is a great potential for MLS to be developed into a real-time URLS system as part of the railway system to enable further railway development.

1.7. Outline of Report

This report is organized for delivering the relevant background information and the direction of research. The outline of this report is summarized in this section.

✓ Outlines organization of report

Chapter 1 Modern Rail Transport – the importance and deficiencies of modern underground railway systems were introduced. The motivation of conducting research in developing MLS towards an URLS solution is originated from the potential benefit after solving a major problem: GNSS replacement.

Use the present simple tense or future tense when explaining the content, i.e. "will be introduced" or "are introduced".

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Chapter 2 Fundamentals of Underground Railway Surveys and Laser Scanning − A brief introduction to monitoring systems, train control systems and signaling systems for underground railways is presented. It is followed by the background of MLS system, such as its development, components, general performance and applications.

Do not state the chapter titles. A brief outline is sufficient.

Chapter 3 Mobile Scanning in Underground Railways − General solutions to GNSS outage are summarized. The concepts of alternatives for URLS solution and corresponding shortcoming will be introduced.

Chapter 4 Potential Development and Applications − It summarizes the areas of potential development if the research objectives are achieved.

Chapter 5 Work to Date − The major studies for the research preparation are summarized, which include the track alignment geometry, train localization, inertial navigation and ***Simultaneous Localization and Mapping*** (SLAM).

Chapter 6 Future Work − The report is concluded by future works, which are planned to be achieved at different stages but might be subject to minor changes.

2. Fundamentals of Underground Railway Surveys and Laser Scanning

Underground railway is a critical environment for train operation, safety enforcement and maintenance of infrastructure, which is used for high-capacity public transport. With the increasing complexity of railway network, the safety conditions of railway tunnel are more significant to human lives.

✓Describes background, although better not to repeat what has been discussed in chapter 1.

In this chapter, general monitoring systems for underground railway tunnels are summarized. The

✓Outlines content of chapter
✓Uses clear topic sentence outlining content of chapter

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fundamentals of Mobile Laser Scanning are also introduced with the general components, performance and applications.

2.1. Monitoring Systems for Underground Railways

Various measurement systems are implemented for tunnel monitoring through geo-technical or geodetic methods. The collection of measurement data would be processed and analyzed by certain statistical methods, or being fed to some models for structural analysis.

Do not be vague, e.g. avoid "some models", "certain statistical methods", better "models used for structural analysis" and "relevant statistical models".

2.1.1. Tunnel Profile Survey

Tunnel profiling, or tunnel profile survey is a conventional method to measure the tunnel dimension through regularly spaced cross sections, which can be used for clearance estimation, checking alignments of ducts and rails, monitoring deformation, compiling as-built drawings, and indicating structural failures etc. (Clarke, 1996).

✓ Outlines content of chapter
✓ Uses clear topic sentence to outline content of chapter

Tunnel profile data can be acquired manually by using reflectorless total station. Point-to-point measurement is conducted at pre-defined sections guided by a laser level meter, which is one of the adopted method for MTR tunnels. Another collection method can be done by laser profiler, such that the tunnel cross section can be automatically measured as a series of points. The geometry and shape of tunnel profile can be better described and analyzed.

State cause and effect, i.e. "This means that the geometry and shape ..."

It has been developed into a dynamic solution consisting of tachometer and laser profiler, which is rail-guided and can provide continuous point cloud along the tunnel.

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2.1.2. <u>Convergence Measurement</u>

The convergence measurement is a very common approach for evaluating the tunnel stability conditions, which is conducted by diametrical or perimetral changes registered by mechanical or optical systems (Gama, 2004). It is usually performed along cross-sections of the tunnel at intervals depending on the instability and to detect abnormal displacements at the circumference of tunnel.

✓ Introduces approach generally in paragraph 1, gives specifics in paragraph 2

Convergence monitoring can be done by intermittent manual measurements, or continuous monitoring with installation of equipment. For example, the distances between reference convergence pins can be manually measured with taps fitted with extensometers (Clarke, 1996); or the deformations can be continuously recorded by extensometric method with sets of electric resistance strain gauges or fiber optics sensors (Gama, 2004).

✓ Gives examples to illustrate approach.

2.1.3. <u>Settlement Monitoring</u>

Settlement monitoring is a general method for ensuring the stability or ground or structure by detecting any unusual change in level. It can be simply done by differential leveling throughout the tunnel, while the level of monitoring points can be determined relative to the reference points. The monitoring points are vertically georeferenced and any significant settlement can be identified from the survey record.

Another approach for settlement monitoring is geotechnical method, such as settlement gauge measurement (Roctest, n.d.). The settlement measurement can be implemented by wide range of design with fiber optic or vibrating wire. The equipment can be directly installed to structure at intervals and perform automatic and continuous monitoring.

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2.1.4. Automatic Deformation Monitoring System

Automatic Deformation Monitoring System (ADMS) is an integrated monitoring solution designed for automatic and continuous operation. For tunnel monitoring, ADMS usually consists of 3-dimensional geodetic measurement by sets of robotic total stations installed along the monitoring section, which are programmed for periodic measurements. Monitoring points are distributed along the tunnel and establish a control network, while 3-dimensional displacements of monitoring points are coordinated and can be further analyzed.

Do not use "For XX, …" structure, a better alternative is "When used in tunnel monitoring, …"

2.2. Limitations of Monitoring Systems

The conventional monitoring systems for underground railways usually focus on the structural health of tunnel through various measurements to reference points. Although the monitoring methods are reliable, precise and sensitive to specific changes, insufficiencies and limitations still exist.

✓ Gives introductory paragraph to section

2.2.1. Installation of Equipment

To enhance the system automation, some monitoring systems require installation of equipment to the tunnel for continuous measurements, which introduce additional installation and maintenance cost. Consequently, it is usual to apply monitoring equipment only for important sections of a tunnel. For example, the ADMS can provide an automatic and periodic solution to 3-

State the main point first, i.e. "The cost of installation and maintenance is a drawback with monitoring…".

Cite references for sources of these limitations.

✓ Summarises main point of paragraph with last sentence.

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dimensional displacement monitoring. However, it usually involves multiple robotic total stations to cover the monitoring network along the tunnel. It is not cost effective to be applied for the whole tunnel, which would cause unnecessary cost for safety enhancement.

As a result, the usual approach for tunnel monitoring is based on preliminary study to the instability of tunnel. For less important or more stable tunnel sections, monitoring works would be minimized.

2.2.2. *Discrete Measurement and Monitoring*

Most of the monitoring measurements are implemented at subdivided sections, while sampling points represent the overall conditions of the tunnel sections. The framework for detecting tunnel deformation is usually established through the limited number of sample measurement. It is possible for the monitoring system to disregard any unusual changes beyond the ambit of measurements.

Use more formal quantifiers, i.e. "The majority of…"

2.2.3. *Mobility of Measurement*

Automation of tunnel monitoring is one of the major advantages of latest generation of monitoring systems, which is the key to real-time operation for maximizing the system efficiency. However, general solutions require installation of equipment to the tunnel for continuous or periodic measurements at static location.

✓Summarises main point of paragraph with last sentence

Some monitoring methods can be applied to multiple location and to minimize the necessity of installation, such as settlement monitoring, or profile surveying. The drawback of enhanced mobility is that most of the methods require manual measurements

Use work as uncountable, i.e. "Focus of Monitoring Work"

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or occupy the tunnel section during measurement, which have lower temporal resolution.

2.3. Focus of Monitoring Works

Various measurements are conducted inside a tunnel for monitoring miscellaneous conditions, such as structural strain, temperature, vertical and horizontal displacement, underground water etc. The structural health of tunnel is monitored and analyzed by integrating available types of information. Monitoring systems focus in detecting significant changes before structural failure occurs and minimize the risk of disaster.

Use infinitive to express reason, i.e. "to monitor".

Use the form "focus on" rather than "focus in".

Most of the tunnel monitoring methods are based on measurements with sampled reference points or alignments for tunnel structure. Nevertheless, these methods cannot detect non-structural displacement or physical changes of other objects inside the tunnel. The non-structural physical conditions of tunnel are usually not being monitored.

✓ Highlights main weaknesses

2.3.1. Potential Risks for Underground Railways

Tunnel structural failure is the main concern for monitoring systems. Safety is always the first priority for railway operation, but minor accidents can also cause serious consequences. Failure due to non-structural causes, such as malfunctions of point machine, undetected falling objects or obstacles, are possible to disrupt the railway operation with service delay, or even collision and derailment. The operation clearance is not being detected by traditional monitoring measurements. However, these types of accident are far more frequently happened than accident caused by structural failures.

Use happen as an active verb, i.e. "these types of accident happen far more frequently than…"

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2.4. Introduction of Mobile Laser Scanning

The MLS system is a potential solution to support tunnel monitoring. In the following sections, the background of MLS technique is summarized in terms of components, performance and limitations.

✓ Gives outline of section

2.4.1. Development of Mobile Laser Scanning

MLS System is developed with the improvement of IMU, LiDAR measurement device and computer technology. Nowadays, various commercial MLS systems are available for surveying purposes with well-developed approach, such as ***RIEGL VMS***, ***MDL Dynascan***, ***IGI StreetMapper*** or ***Trimble MX8*** etc, which can achieve centimeter to decimeter level of accuracy and are gradually adopted as alternative large-scale mapping solutions such as surveying highways, tunnels, railways or urban cities etc.

Use present perfect tense to discuss recent developments, i.e. System has developed"
Do not start a sentence with "nowadays" better "various commercial MLS systems are now available..."

Do not bold the text for key words.

The fundamental concept of MLS originated from ***Airborne Laser Scanning*** (ALS) during the mid-1970s. The ALS prototype was developed by the ***National Aeronautics and Space Administration*** (NASA) for military purposes (Shan and Toth, 2008), and consists of ***Global Positioning System*** (GPS) device, an IMU and a LiDAR measurement device. The first commercial ALS system became available in 1994 (Juha Hyyppä, 2011) and development has continued to the point where today's systems are capable of measuring at rates of 800kHz (RIEGL, 2014) with point precisions of 20 mm.

✓ Uses present perfect tense to discuss Development, e.g." has continued"

During 1990s, the concept of ALS was applied to land-based solution called the ***Mobile Mapping System*** (MMS). It is

✓ Lists previous studies and development of system
✓ Discusses strengths of new developments, e.g. "fast and cost-effective"

designed as multi-sensor or multi-platform system, which is the technological development trend as fast and cost-effective data acquisition (El-Sheimy, 2005). With more compact LiDAR devices, land-based ***Mobile Laser Scanning*** system became available in the late-1990s (Puente et al., 2011). The integrated LiDAR device become the core component for later generation of mapping system to achieve higher efficiency of data acquisition.

2.5. Basics of Mobile Laser Scanning

A general MLS system consists of navigation devices and mapping devices that originated from ALS and improved by instrument technology.

2.5.1. INS/GNSS Solution

Inertial Navigation System is the core component for the navigation solution of MLS. It serves for the navigation trajectory with high frequency 3-dimensional position and orientation updates, which is a time tagged record for geo-referencing the laser scanning data, images or other available measurements.

✓ Introduces key system and outlines main features

Inertial navigation employs measurements of IMU for tracking the corresponding rate of rotations and accelerations. Generally, INS can provide high update rates and precise position and orientation. However, it suffers from “drift” and systematic biases which reduce long-term navigation accuracy. The principles and properties of IMU for inertial navigation would be summarized in Chapter 5.3.

Cite source for technical information.

Global Navigation Satellite System (GNSS) is an integrated satellite positioning technique, which provides 3-dimensional position with various processing approaches. It is widely applied to MLS systems

✓ Highlights strengths and weaknesses of system and compares two systems

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for INS error control. Although GNSS has lower update rates, but the overall accuracy can be maintained throughout survey.

High-end system combined the INS and GNSS into an integrated INS/GNSS navigation system, or the ***Position and Orientation System*** (POS), to control the navigation and is usually processed with Kalman filtering. The advancement in INS/GNSS integration can provide flexible solution for controlling the trajectory of MLS system with acceptable accuracy even if GNSS signal is lost for short period of time.

✓Places adverb next to verb, e.g. "usually processed", "commonly applied"

2.5.2. Distance Measuring Indicator

In order to minimize the accumulation of navigation errors and integration errors, a wheel-mounted ***Distance Measuring Indicator*** (DMI) is commonly applied for accurate velocity updates (Puente et al., 2011), which is significant to accuracy maintenance during GNSS-outage. Additional sensors can be integrated to the navigation solution through the error model definition.

2.5.3. Digital Camera

Digital camera is the fundamental mapping sensor, such that the INS/GNSS provides a direct geo-reference solution for acquiring 3-dimensional spatial data by through photogrammetry. The instrumental cost of digital camera is relatively low and the photogrammetric orientation solution had been well-developed. Digital camera is still the most commonly used passive mapping sensor.

Ensure key terms are countable or uncountable. Camera is countable, i.e. "Digital cameras".

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2.5.4. LiDAR Measurement Unit

✓ Compares two techniques using adverbs to generalise, e.g. "usually have Larger", "are generally more accurate"

LiDAR measurement unit, such as laser scanner or laser profiler, is an active mapping sensor and is the fundamental mapping sensor for a MLS system. There are two general techniques for LiDAR measurement: ***Time-Of-Flight*** (TOF) and phase shift. TOF scanners usually have larger measurement range, while phase-based scanners are generally more accurate. The laser Pulse Repetition Rate (PRR) is one of the factors to determine LiDAR data collection rate (Ussyshkin and Boba, 2008). General commercially available scanners have PRR of 50 kHz – 500 kHz and are able to maintain the required point density at high vehicle speeds (Puente et al., 2011).

Point cloud is generated from geo-referencing the LiDAR profile data with the platform motion, such that the point cloud density partially depends on the vehicle speed. In addition, feature extraction and its accuracy rely on the geo-reference performance.

2.6. Principles of Mobile Laser Scanning

General MLS systems are capable of providing a geo-referenced solution for mapping data. The fundamental principles of MLS operation can be divided into three major parts, which are summarized in this section.

2.6.1. Navigation Solution

✓ Gives clear topic sentence

The navigation solution for general MLS systems is implemented through INS/GNSS integration. The data collection (inertial measurement and GNSS positioning), data processing and filtering are usually independently conducted within the navigation system. **Figure 1** and **Figure 2** illustrate the data collection and process for an INS, and the integrated INS/GNSS configuration respectively.

Do not use bolded text for the name of figures.
✓ Refers to figures in text, i.e. "Figure 1 and 2 illustrate"

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After processing, the estimation of positions and attitudes is recorded as the navigation trajectory and time tagged, which can be used for geo-referencing the mapping data.

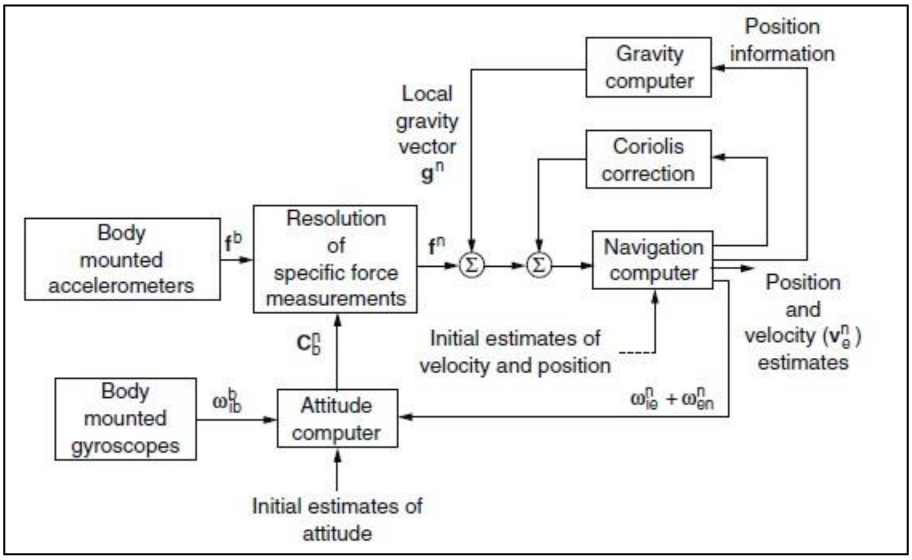

Figure 1: Data Process for an INS (Titterton and Weston, 2004)

✓ Numbers figure
✓ Gives figure title
✓ Cites source

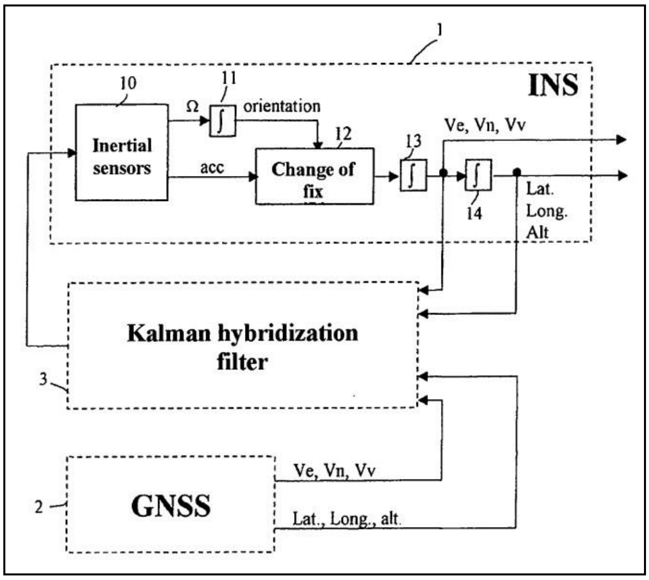

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Figure 2: Hybrid INS/GNSS System (Coatantiec and Lesot, 2007)

2.6.2. Geo-Reference Solution

Mapping data, such as images or LiDAR profiles, are stored with its coordinate frame and time tagged. The geo-referencing process for the mapping data is implemented through several transformations, which requires the positions and attitudes through interpolation from time tagged trajectory. **Figure 3** shows the relationship between different coordinate frames, including the sensor frame, body frame and mapping frame.

✓ uses range of verbs to refer to figures, i.e. "illustrates" and "shows" and "In Figure 1…"

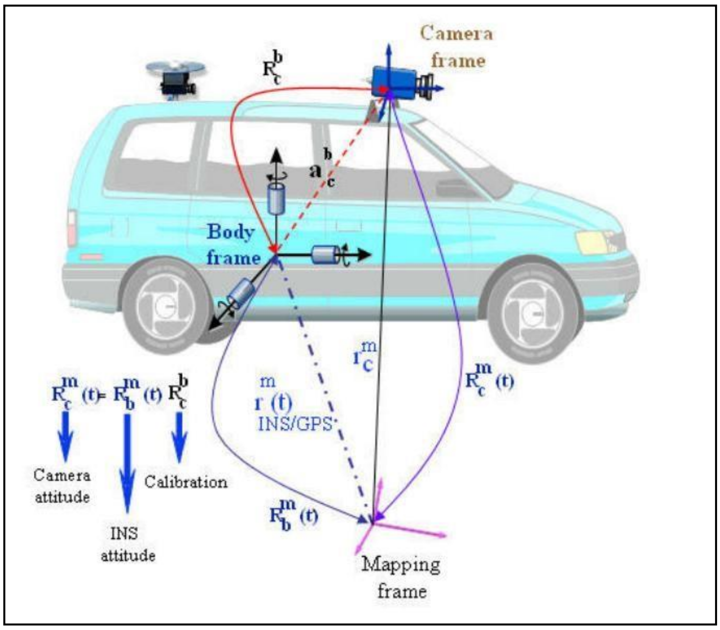

Figure 3: Relationship between Coordinate Frames (Hassan et al., 2006)

Equation 1

$$\mathbf{r}^m = \mathbf{r}_b^m(t) + \mathbf{R}_b^m(t)[s\mathbf{R}_c^b\mathbf{r}^c + \mathbf{a}_c^b]$$

where $\mathbf{r}^m$ is the 3-dimensional coordinates of the point in mapping frame; $\mathbf{r}_b^m(t)$ is the coordinates of IMU in mapping frame; s is the scale factor corresponding to the point; $\mathbf{R}_b^m(t)$ is the rotation matrix from body frame to mapping frame; t is the time of image capture; $\mathbf{R}_c^b$ is the rotation matrix representing the misalignment between

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camera and IMU; $\mathbf{r}^c$ is the image coordinates; $\mathbf{a}_c^b$ is the linear offset between camera and the body frame.

Equation 1 illustrates the geo-referencing solution for images, while the rotation matrix $\mathbf{R}_b^m(t)$ and position vector of IMU $\mathbf{r}_b^m(t)$ are interpolated from time tagged navigation trajectory.

2.6.3. System Calibration

To establish the coordinate frames and their relationship, system calibration is required for achieving the geo-reference solution. In **Equation 1**, the rotation matrix for the misalignment between camera and IMU $\mathbf{R}_c^b$ and the linear offset between camera and IMU $\mathbf{a}_c^b$ are the constant values to be estimated before the geo-reference solution can be implemented. Therefore, system calibration is necessary to establish the relationship between different coordinate frames, which can be conducted by several approaches (Rieger et al., 2008; Chan et al., 2013).

Use "to" + verb to express purpose, i.e. "is required to achieve…"

2.7. Performance of Mobile Laser Scanning

The overall accuracy of general MLS systems depends on the error propagation with navigation errors and measurement errors through geo-referencing.

Do not use an introductory subsection when the section is very short.

2.7.1. Performance under General Conditions

Nowadays, the laser scanners or laser profilers can provide millimeter to centimeter level of precision depending on hardware quality (Kaartinen et al., 2012). However, the absolute accuracy of measurement is constrained by the geo-reference solution through the INS/GNSS trajectory, which mainly depends on the GNSS

Do not start the sentence with "Nowadays". "Modern laser scanners or laser profilers can provide… is more appropriate.

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and IMU data. Most of the systems can reach an accuracy of centimeter level with good GNSS conditions (Haala et al., 2008; Juha Hyyppä, 2011; Kaartinen et al., 2012), but the geo-reference error for horizontal position can reach meter level under degraded GNSS conditions (Haala et al., 2008).

2.7.2. Uncertainty for GNSS-outage Condition

In GNSS-outage areas, standalone INS serves for position and orientation updates with minimum external controls, such as DMI velocity updates. For high quality IMU, the short-term navigation precision is relatively acceptable with millimeter to centimeter level within a minute, but the long-term accuracy would be rapidly degraded by propagated sensor errors and navigation errors. As the system errors for INS are time dependent and accumulative. The overall accuracy of a MLS system is typically bounded by the performance of navigation solution (Puente et al., 2011).

✓ Describes background and details system in paragraph 1

The GNSS device is the core component for INS error control. Its positioning accuracy and stability is highly dependent upon the working environment and directly affects the overall data accuracy. Experiments had been conducted to analyze the impact of standalone INS on the accuracy of MLS systems. Results showed that the positioning errors can exceed tens of meter over a period of minutes for standard IMU (Klein and Filin, 2011; Boavida et al., 2012). Although the deficiency of GNSS dependence can be minimized by extreme quality of IMU, it is the fundamental limitation of MLS technique to be solved.

✓ Highlights shortcomings of system in paragraph 2

✓ Explains possible solution
✓ Evaluates possible solution

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2.8. Mobile Laser Scanning in Railways

The use of terrestrial laser scanning technology had extended the survey industry with extreme measurement details, while the MLS technique further enhances the availability and the efficiency of data collection. The accuracy of MLS is rapidly growing in the last few years with the improvement of sensor technology and processing technique. More applications became available with proven accuracy or by alternative control for in the case of GNSS-outage. MLS applications in railways, such as rail track and overhead powerline surveys or tunnel surveys, can replace conventional survey methods and reduce time and inconvenience. Consequently, MLS systems are becoming more frequently used in railway industry.

Do not use the past perfect tense, e.g. "had extended". Use the present perfect tense when there is no exact time, i.e. "has extended" and "has been rapidly growing".

2.8.1. Existing Applications in Railways

As-built surveys, clearance studies or structure monitoring are the main applications for railways using MLS systems (Yen et al., 2010; Kremer and Grimm, 2012; Boavida et al., 2012, which are important issues to safety and asset management. Railway measurements, such as track alignment, rail profile, crossings, asset inventory, bridges, tunnels or terrain, become common applications available for survey-grade MLS systems (Terrametrix, 2013).

Use "e.g." or "see for example" if you do not list all the citations, i.e. (see for example, Yen et al., 2010; Kremer and Grimm, 2012; Boavida et al., 2010).

RailMapper is one of the well-known systems available for various railway applications, which had been selected by ***Terrametrix*** and performed a number of rail mapping projects with acceptable quality. ***Riegl VMX-250/ VMX-450 Rail*** is another MLS system designed for railway

Include a topic sentence, i.e. "A number of MLS systems have been used for railway applications"

✓ Uses present perfect tense to describe recent developments, i.e. "has developed"

-

applications. It was selected by France's rail network operator ***SNCF*** (Société Nationale des Chemins de fer Français) for maintaining and monitoring railway infrastructure through a program of continuous or even repeated 3-dimensional monitoring and inspection (McGovern, 2013). ***Fraunhofer IPM*** has developed a simplified MLS system for railway measurement such as monitoring the condition of rail networks and moving trains. The measurement systems consist of contact wire recording, wire wear monitoring, laser pole detection, clearance profile scanning, high speed profiling, sector profile scanning or pavement profile scanning ("Mobile Laser scanning...," n.d.). A similar concept is adopted for obstacle detection system, which does not rely on inertial navigation reference (Weichselbaum et al., 2013).

The use of MLS for railway measurement is a potential development for continuous or periodic operation. It is also possible to be part of a ***Positive Train Control*** (PTC) project described by the American Railway Engineering and Maintenance-of-Way Association (Whitfield, 2013), such as train collision avoidance, line speed enforcement, speed restrictions, and rail worker wayside safety.

2.8.2. Limitations of MLS Configuration

The MLS systems for railway measurement usually adopts very high quality of inertial sensor and various methods to overcome intermittent GNSS outages, such as sudden loss of GNSS connection in urban area, or maintaining INS accuracy inside tunnels.

Include the main idea in the opening paragraph as well as in the subtitle, i.e. "There are a number of problems associated with the use of MLS in railway systems.

In underground railways, the system cannot rely on GNSS positioning for initialization and operation stages. Alternative control methods are critical, while there are numerous operational problems for day-to-day application

Clearly link cause and effect, i.e. "As the system cannot rely on GNSS positioning in underground railways, alternative control ..."

-

such as system initialization and closed-loop adjustment without GNSS positioning; on-site misalignment calibration; and back-up solutions for INS, GNSS replacement and navigation error control.

MLS systems with general configuration are designed as multi-platform system for independent survey projects to maximize the availability and cost efficiency. Finite systems are designed for railway environment with high performance INS/GNSS and specific processing software, but none have been specifically developed for use in environments such as in underground tunnel systems where GNSS is not available.

✓ Highlights research gap, e.g. "none have been specifically designed..."

Finding a solution to this problem will make MLS an extremely valuable tool for the management of underground railway systems and the provision of safe, reliable and efficient transportation services.

✓ Explains value of this study, e.g. "extremely valuable tool"

End chapter 2 with a short summary and a link to the next chapter, i.e. Chapter three will discuss..."

3. Mobile Scanning in Underground Railways

The development of GNSS-free solution for Mobile Laser Scanning would be beneficial to achieve consistent accuracy and able to be operated independent to GNSS conditions. In general, the quality of MLS measurements highly depends on the GNSS availability. Although commercial MLS systems have been successfully deployed in above-ground railways that contain long tunnels, GNSS replacement is still an important consideration for underground railways.

✓ Outlines structure of following chapter

-

In this chapter, general solutions for GNSS outage are summarized. It is followed by some specific strategies and approaches designed for MLS in underground railway.

3.1. General Solutions to GNSS Outage

The accuracy loss due to GNSS-outage is a critical concern for MLS systems with low-cost IMU and a large concern for those with high-end IMUs. Several solutions are commonly adopted as conventional approaches to overcome the problems. Results have shown that the overall accuracy is significantly improved by the approaches from tens of meter to decimeter or centimeter level accuracy (Boavida et al., 2012; Klein and Filin, 2011). In this section, general approaches to solve the problems of GNSS-outage are summarized.

> Use the researcher's name as the subject if their studies are important, i.e. "Boavida et al. (2012) and Klein and Filin (2011) have shown that ..."

3.1.1. Independent Velocity Updates

For free inertial operation, position is updated from the transformed displacement estimated from double integration of acceleration through accelerometer output with previous velocity and position. Position errors accumulate from double integration of acceleration errors, integration of velocity and position errors from the previous state. External sources of velocity measurements are critical for standalone INS for the maintenance of velocity and position updates.

> State the main point first, e.g, "For free inertial operation", is not the main point of the paragraph or section, i.e. "The main cause of position error is..."

A DMI is one of the usual instruments employed for independent velocity measurements of land-based MLS systems, which is usually implemented by a wheel-mounted odometer installed to vehicle. It is not an essential component under general GNSS conditions, but provides better velocity update or ***Zero Velocity Update*** (ZUPT) control. Independent velocity

-

update control is a back-up solution for GNSS-outage operation, which is irreplaceable for accuracy maintenance supporting the inertial navigation.

Nevertheless, this approach can only control the accumulation of velocity errors from integration of acceleration, but not the accumulation of position errors. For specific MLS applications, velocity updates control can be implemented by different techniques or approaches, which reduces the GNSS-outage problem instead of being a complete solution.

3.1.2. Error Control for bridging GNSS Outage

The error control for bridging GNSS outage is a processing technique applied to reset the INS with Kalman filter estimated parameters by combining and smoothing the forward and the backward Kalman filter (Mostafa et al., 2001; Thies, 2011). It is usually applied to MLS systems for initialization and finalization with GNSS positioning to adjust INS errors during GNSS-outage. **Figure 4** illustrates the concept of forward and backward Kalman filtering, the errors are minimized with the assumption of even distributed errors. It can be used for MLS survey in long tunnels to achieve acceptable results with available system components or other integrated solutions (Boavida et al., 2012).

✓ Structures subsection clearly

a. Introduces system
b. Explains how system works
c. Describes limitations with the system

-

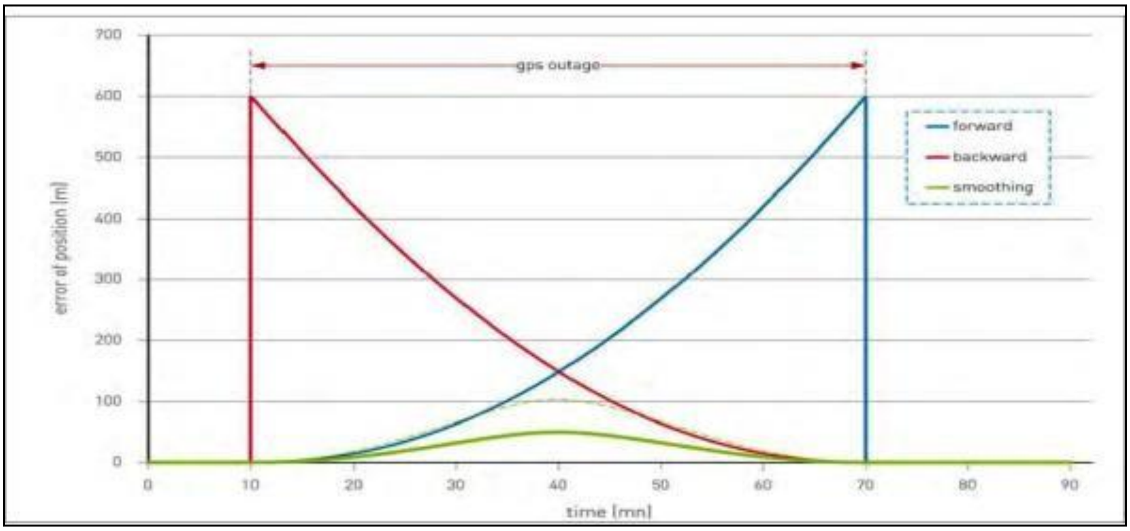


Figure 4: Error Control by Forward and Backward KF (Thies, 2011)

The processing technique is widely used for bridging the gap of GNSS-outage with the INS errors are estimated through post-processing. It is essential to MLS system for error estimation during long-term GNSS-outage. However, any undetected error would still be accumulated within the GNSS-outage period and it cannot be independently applied to solve the problems of stand alone INS.

✓ Signposts limitation with system clearly,
e.g. "however"

3.1.3. Land Mark Update

Land Mark Update method aims at correcting the vehicle position with measurement to land marks or control features (Imanishi et al., 2011; Klein and Filin, 2011). The measurement is usually realized by photogrammetric or laser scanning measurement as a post-processing solution to maintain accuracy at GNSS-outage areas. Control features can be any identifiable marks or sharp features, which are extracted from measurement with known position. The quality of this solution depends on control accuracy, measurement by MLS, and the available intervals of control features.

✓ Uses clear topic sentence
✓ Structure:
a. Paragraph 1 description
b. Paragraph 2 evaluation

-

It is widely adopted for maintaining the overall accuracy, since the position errors of control features are independent of the INS navigation. It is an implementation of ***Coordinate Updates*** (CUPT) for resetting the INS estimated position through the MLS measurements, such that the navigation errors can be bounded. However, time and cost is usually required for control feature installation or/and independent survey.

3.1.4. Photogrammetric Bridging

Photogrammetry is a conventional technique to reconstruct 3-dimensional information form stereo-image pair, which can be applied to bridge the gap of GNSS-outage through relative orientation of image pairs (Roncella et al., 2005; Hassan et al., 2006; Bayoud et al., 2004). Under normal conditions, INS/GNSS is used for navigation updates and determining the camera ***Exterior Orientation*** (EO) parameters through the Kalman filter processing. When GNSS is not available, photogrammetric adjustment can update the EO parameters through the relative orientation of stereo-overlapped images, which provides independent measurements to INS error estimation. The position and orientation of system platform can be better controlled from photogrammetric measurement until GNSS positioning is available. Similar concept from video camera, videogrammetry, is also a common solution for some MLS systems (Chaplin, 1999; Hunter, 2009).

Use articles and plurals with key words in the text, i.e.

the orientation

photogrammetric measurements

..........video cameras

Use strong subjects, i.e. "Another common solution for...is videogrammetry, which is a similar concept using cameras.

Photogrammetric bridging is a vision-based solution, which is a common solution for MLS systems with the development of automatic image processing, feature extraction and processing techniques. It has the merit that the matched tie points are not necessarily known control points. However, it cannot maintain long term accuracy,

✓ Highlights strengths and weaknesses of system. e.g. "it has the merit of...'

-

while the quality of navigation maintenance would be limited by environmental illumination that is typically poor in railway tunnels.

3.2. Localized Tunnel Projection

Inertial navigation can usually maintain short-term precision depending on IMU quality and duration. For certain purposes, the relative precision within a segment of point cloud data is good enough for describing the mapping object.

Avoid informal language, e.g. "good enough", use formal words, i.e. "sufficient"

By applying MLS to tunnel survey, the tunnel geometry can served as nominal constraint for adjusting navigation trajectory and localizing the mapping data (Gonçalves et. al., 2012). Point cloud segmentation is done for independent trajectory adjustment with tunnel geometry, while the whole tunnel is divided into different sections for storage and analysis.

The concept of projection can simplify the adjustment and the representation of measurement result. It is designed for tunnel survey and can work in GNSS-free railways, but it does not provide solution to maintain absolute accuracy of measurement.

Use "s" with countable nouns, i.e. "the measurement of results" and "provide solutions".

3.3. Rail-bounded Inertial Navigation

In a railway environment, fundamental positioning of a train relies on the alignment of the rail track which can be used as a continuous control feature to serve for CUPT and may substitute the GNSS component. Since a train's movement is pre-defined and bounded by the rail track, the position of a train can be reduced to 1-dimensional navigation from alignment data and alignment chainage (the centerline distances

✓ Explains technical terms using bracketing as they are introduced, i.e. chainage (the centerline...)."

-

from a specific point in the alignment). The position can be extracted for INS process if navigation distance is accurately determined.

By referring to the track geometry, position of train axles can be determined. However, the train car is not a rigid body and the relative rotations and linear motion of a reference axle would be different from that of the upper train body where the MLS system components would be attached. Employment of track alignment geometry alone is not enough and relative motions between a reference axle and the MLS system are also required.

Use present simple tense to describe things that are fact and not "would", i.e. "components are attached".

3.3.1. Navigation in Non-curved Sections

Try and link subsections. Refer either to the next section or the previous section, i.e. "The causes of the relative motion will be discussed in the next section".

Various factors are possible to cause relative motion between the axle and the train body, such as train accelerations, passenger movements, vibration at track junctions, rail defects etc. Nevertheless, turning at curve would introduce the main component of the motion, while the motion caused by other factors might be less significant.

For non-curved section, the 3-dimensional offsets between IMU centre and the reference axle centre are relatively stable without a centripetal acceleration. The reference axle position can be used for CUPT for INS process and resetting the offsets in such sections.

If the offsets are stable, the relative coordinates are constant values in body frame. The offset can be transformed into navigation frame through the parameters from INS computation. The coordinate differences between reference values from alignment and measured values from INS can be determined through **Equation 2**.

-

Equation 2

$$\begin{bmatrix} x_{ref}^n - x_{ref,ins}^n \\ y_{ref}^n - y_{ref,ins}^n \\ z_{ref}^n - z_{ref,ins}^n \end{bmatrix} = \begin{bmatrix} x_{ref}^n \\ y_{ref}^n \\ z_{ref}^n \end{bmatrix} - \left(\begin{bmatrix} x_{imu}^n \\ y_{imu}^n \\ z_{imu}^n \end{bmatrix} + \mathbf{C}_b^n \begin{bmatrix} x_{imu2ref}^b \\ y_{imu2ref}^b \\ z_{imu2ref}^b \end{bmatrix} \right)$$

where

$[x_{ref}^n \quad y_{ref}^n \quad z_{ref}^n]^T$ is the position of reference from alignment in navigation frame;

$[x_{imu}^n \quad y_{imu}^n \quad z_{imu}^n]^T$ is the IMU position updated through INS in navigation frame;

$[x_{imu2ref}^b \quad y_{imu2ref}^b \quad z_{imu2ref}^b]^T$ is the offset between IMU and reference in body frame;

$\mathbf{C}_b^n$ is the transformation from body frame to navigation frame updated through INS;

$[x_{ref,ins}^n \quad y_{ref,ins}^n \quad z_{ref,ins}^n]^T$ is the position of reference computed from INS in navigation frame.

By considering the same amount of position errors at reference point and IMU center, the coordinate differences can be input to INS Kalman filter as measurement to position error for CUPT.

3.3.2. Navigation in Curved Sections

✓ Clear topic paragraph outlining Section

Avoid the weak topic, e.g. "For the rail track…"

For the rail track section with horizontal curvature, the orientation of IMU and its offsets to reference axle would change. It is caused by the compensation architecture for axles to minimize the vibration of train car body, such that the whole train is not a rigid body for applying the track alignment position to the IMU of MLS system.

3.3.3. Navigation Record in Alignment Frame

In addition to constant offset, a dynamic offset exists due to alignment curvature or train vibration. The offset modeling can be further extended to cover the constant offset and dynamic offset in alignment frame. Such that the dynamics of rail-bounded INS can be described as:

-

Equation 3

$$\begin{bmatrix} x^n_{imu,ref} \\ y^n_{imu,ref} \\ z^n_{imu,ref} \end{bmatrix} = \begin{bmatrix} x^n_{ref} \\ y^n_{ref} \\ z^n_{ref} \end{bmatrix} + \mathbf{C}^n_a(d_{ch}) \left(\begin{bmatrix} x^a_{ref2imu} \\ y^a_{ref2imu} \\ z^a_{ref2imu} \end{bmatrix} + \begin{bmatrix} \Delta x^a_{ref2imu}(d_{ch}) \\ \Delta y^a_{ref2imu}(d_{ch}) \\ \Delta z^a_{ref2imu}(d_{ch}) \end{bmatrix} \right)$$

where

$[x^n_{imu,ref} \quad y^n_{imu,ref} \quad z^n_{imu,ref}]^T$ is the position of IMU from reference alignment

$[\Delta x^a_{ref2imu}(d_{ch}) \quad \Delta y^a_{ref2imu}(d_{ch}) \quad \Delta z^a_{ref2imu}(d_{ch})]^T$ is the dynamic offset in alignment frame;

$\mathbf{C}^n_a(d_{ch})$ is the dynamic rotation from alignment frame to navigation frame.

The dynamic offsets and rotations can be estimated and recorded with chainage based on constant offsets and rotations. The constant component of offsets and rotations can be determined when the train is oeprated at non curved sections. The rotations between navigation frame and alignment frame can be defined by an additional angle about the local vertical axis.

Refer to Equation 4 in the text, "as shown in Equation 4:"

Equation 4

$$\mathbf{C}^n_a = \begin{bmatrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

where α is the rotation for maintaining the tangent bearing of alignment frame and the north direction.

For the same train to run along the same rail track sections, the offsets between the reference axle and the IMU would be similar due to physical interaction between the train and the rail track. After post-processing, the offsets can be adjusted, recorded with respect to alignment chainage, and applied to future operation for updates and adjustment. It can be modeled by polynomial or recorded with nominal intervals through interpolation.

-

3.3.4. Implementation of Coordinate Updates

The rail-bounded navigation can be implemented by ***Coordinate Updates*** (CUPT) through Kalman filter processing. The differences between the INS derived position and the reference position are input to the INS computation model.

Equation 5

$$\mathbf{z}_{ext}^{n} - \mathbf{z}_{INS}^{n} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \mathbf{X}_c(t) + \mathbf{N}_c(t)$$

where $\mathbf{z}_{INS}^{n}$ is the position vector derived by INS; $\mathbf{z}_{ext}^{n}$

is the position vector derived by external device;

$\mathbf{X}_c(t)$ is the error state of INS position; $\mathbf{N}_c(t)$ is the

noise of position.

3.4. Dual-IMU Coupled Navigation

The previous approach is designed for ideal conditions such that the track geometry data is absolutely accurate or relative motion between the reference axle and train body is consistent for repeating runs. It can be modified by using dual-IMU architecture for the navigation with one IMU (IMU-A) installed at the reference axle and another IMU (IMU-B), attached to the MLS system or upper train body.

3.4.1. Inertial Navigation for Reference Axle

Link 3.4, 3.4.1, and 3.4.2 into a single section, the ideas are very closely linked and it would be easier for the reader.

For IMU-A, it serves for rail track measurement to overcome the uncertain motion of reference axle with respect to the rail track geometry, such that the accuracy requirement for the track alignment data can be loosen.

-

By this approach, the navigation solution from IMU-A should be closely matched with alignment data. The local difference due to structural imperfection can be maintained through IMU measurements, while the overall navigation errors from INS can be constrained by the rails. As a result, the transformation between body frame (IMU-A) and navigation frame can be better controlled and acted as the reference trajectory for CUPT. Since a nominal trajectory is available, a linearized Kalman filter can be applied for efficient computation.

3.4.2. Inertial Navigation for MLS

For IMU-B, it works for the MLS system in free space. By considering the additional constraint of position offsets between IMU-B and IMU-A. Such that the equation can be modified as:

Avoid unclear subjects. It's not clear what "it" refers to. If "it" refers to "IMU-B then it is a double subjects, i.e. "IMU-B works for..."

Equation 6

$$\begin{bmatrix} x^a_{ref2imu} \\ y^a_{ref2imu} \\ z^a_{ref2imu} \end{bmatrix} + \begin{bmatrix} \Delta x^a_{ref2imu}(d_{ch}) \\ \Delta y^a_{ref2imu}(d_{ch}) \\ \Delta z^a_{ref2imu}(d_{ch}) \end{bmatrix} = \mathbf{C}^b_n(d_{ch}) \begin{bmatrix} x^n_B - x^n_A \\ y^n_B - y^n_A \\ z^n_B - z^n_A \end{bmatrix}$$

The loosely-coupled approach can be done through the position updated from two IMUs separately. The constant offset for the two IMUs can be estimated and expressed in body frame (IMU-A) or alignment frame with dynamic offsets as stored as record. The two independent body frames (IMU-A and IMU-B) can be initialized by motion in straight line by transformation between body frames and navigation frame.

Equation 7

$$\mathbf{C}^B_A = \mathbf{C}^B_N \delta \mathbf{C}^N_N \mathbf{C}^N_A$$

By this approach, the dynamic rotations between two IMUs can be estimated through **Equation 7**. The transformation between two body frames should be constrained with rotations caused by train body motion, $\delta \mathbf{C}^N_N$ with respect to historical record.

-

3.5. *Stationary Position Updates*

When the train stops at station, the approximate position of train axle is relatively accurate with the existing approach. The longitudinal position error of the reference axle and the alignment can be measured in 1-dimensional displacement with respect to a point with accurate chainage.

Have an introductory sentence that explains the content of the section.

3.5.1. Optical Method

The concept of digital level instrument can be applied for measuring the displacement of sensor to a reference with horizontal pattern of bar code. The bar code pattern can be placed horizontally along the direction of alignment, which is measured and encoded by a train-borne digital optical instrument. As a result, variation between the stopping position of train and the reference chainage can be accurately determined to re-initializing position.

✓ Uses passive voice with modal verbs to show both objectivity and possibility, e.g. "can be applied"

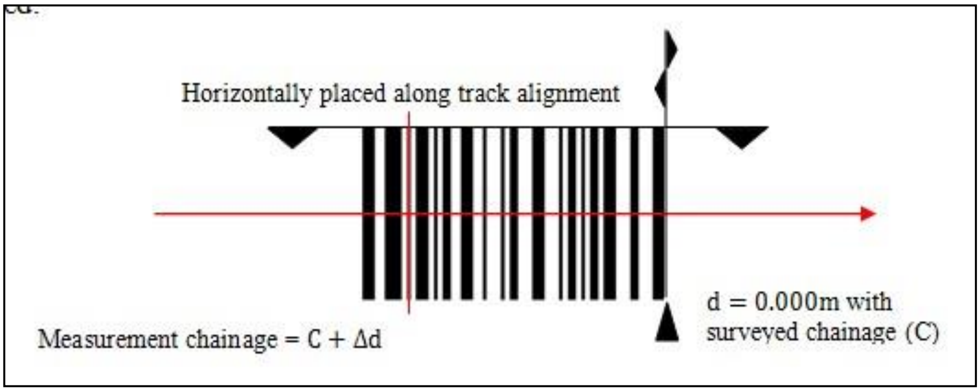


Figure 5: Conceptual Configuration for the Optical Displacement Measurement

3-dimensional position can be recovered from measured chainage with alignment. Thus, position can be updated for reference axle and maintain the performance of INS.

-

3.5.2. *Target Matching Method*

For 3-dimensional positioning, three or more control points are required for constructing a transformation for adjustment. However, it can be simplified by using single control for positioning with alignment in railway environment. Passive targets can be installed and surveyed with chainage, such that signals can be reflected for a train-borne device to measure ranges.

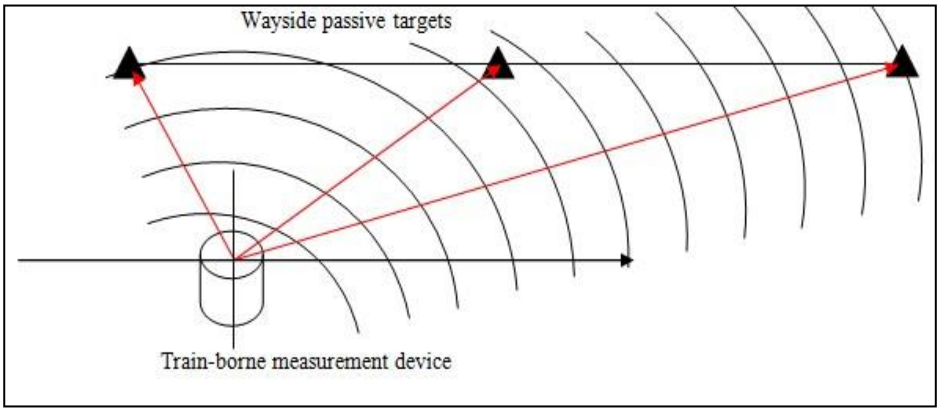


Figure 6: Conceptual Configuration for the Target Matching Measurement

Figure 6 illustrates the configuration of the method, such that the measurement device can track the ranges to multiple targets. A train would decelerate and slow down when approaching a station. It enables the device to determine any change point for distance measurements. The chainage of the measurement device can be accurately estimated by simply detecting the shortest range measurement to any reference target.

Be consistent with the use of tense. e.g. "Would decelerate" is hypothetical, but "enables" refers to what happens in practice. State "a train decelerates and slows down… It enables…"

-

3.6. *LiDAR-supported Inertial Navigation*

In addition to the standalone INS control with track alignment, LiDAR measurement can be integrated into the navigation process for attitude aiding with continuous rail track as control feature as shown in **Figure 7**.

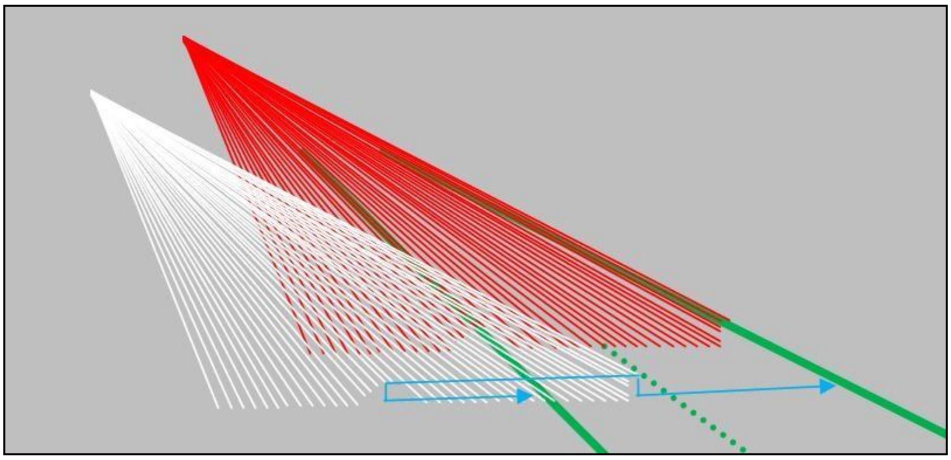


Figure 7: Position Control by LiDAR Data

From the scanning data, the two rail tracks can be extracted and compared with position estimated from alignment data (position of center line, tangent bearing, gradient, super-elevation and rail track offsets). The transformation estimated from the rail track measurement can be used for CUPT.

Avoid "From the scanning data". State "The scanning data allows the …"

Equation 8

$$\mathbf{r}_{ref}^{n} = f(\mathbf{r}_{LiDAR}^{n}, Alg)$$

$$\mathbf{T}_{LiDAR}^{ref} = T\left(\mathbf{r}_{LiDAR}^{n}, \mathbf{r}_{ref}^{n}\right)$$

where $\mathbf{r}_{LiDAR}^{n}$ is the rail track position measured in navigation frame; Alg is the alignment information; f is the function for projecting the rail track position onto the alignment; $\mathbf{r}_{ref}^{n}$ is the projected rail track position and

-

served as reference; T is the function of transformation from

measurement to reference; $\mathbf{T}_{LiDAR}^{ref}$ is the set of transformation parameters.

The mismatched position and attitude errors along the perpendicular direction to the navigation direction can be detected and adjusted, but the errors along the track direction cannot be detected.

✓ Ends section with key features of system clear topic sentence.

3.7. Velocity Updates Control

Although the attitude and lateral position can be controlled with track geometry, position and velocity errors along the rail track is still uncertain. The accumulation of velocity errors and position errors would gradually increase with the propagation of acceleration errors. For implementation of general MLS systems, free inertial is not suggested for long-term navigation as the growth of errors cannot be controlled and has to be aided by additional correction or sensors.

✓ Leads into section 3.7.1 by ending introductory paragraph with topic of next section, e.g. "additional correction or sensors" = "velocity updates"

3.7.1. Velocity Updates/ Zero Velocity Updates

Velocity Updates or ***Zero Velocity Updates*** (ZUPT) is an important technique for resetting the velocity errors of inertial navigation. ZUPT can be done in real-time train operation when stopping at stations or before the junctions, which is easily implemented through Kalman filter processing without requirement of additional equipment at intermittent updates. With external velocity information, continuous velocity updates can be done for minimizing the accumulation of velocity errors.

✓ Gives evaluative comments on system, e.g. "easily implemented"

3.7.2. Traditional Velocity Control

For tracking the motion of train, traditional approaches are done by 0-dimension positioning

-

(intermittent localization) or 1-dimension positioning (continuous distance tracking). Tachometers, or other devices are usually installed to trains for the measuring vehicle velocity, while the navigation distance can be obtained through the integration from velocity. Such that, a continuous velocity control can be applied to the INS by utilizing the existing velocity measurement devices.

From the total velocity of vehicle, the velocity components in 3-dimensional space can be decomposed with respect to the navigation direction.

Refer to the equation in the text, i.e. "The velocity is calculated as follows:"

Equation 9

$$\mathbf{v}^n_{external} = \mathbf{u}^n_{INS} v_{tachometer} = \frac{\mathbf{v}^n_{INS}}{\|\mathbf{v}^n_{INS}\|} v_{tachometer}$$

where $\mathbf{u}^n_{INS}$ is the unit vector of $\mathbf{v}^n_{INS}$; $\mathbf{v}^n_{INS}$ is the velocity vector derived by INS; $\mathbf{v}^n_{external}$ is the velocity vector from external device.

3.7.3. *Implementation of Velocity Updates*

The ZUPT or velocity updates can be implemented with Kalman filter processing. The differences between the INS velocity outputs and the external velocity measurements along the three orthogonal directions are input to the Kalman filter. It can be directly inserted to INS computation model.

Equation 10

$$\mathbf{v}^n_{external} - \mathbf{v}^n_{INS} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \mathbf{X}_v(t) + \mathbf{N}_v(t)$$

-

where $\mathbf{X}_v(t)$ is the error state of INS velocity; $\mathbf{N}_v(t)$ is the noise of velocity measurement.

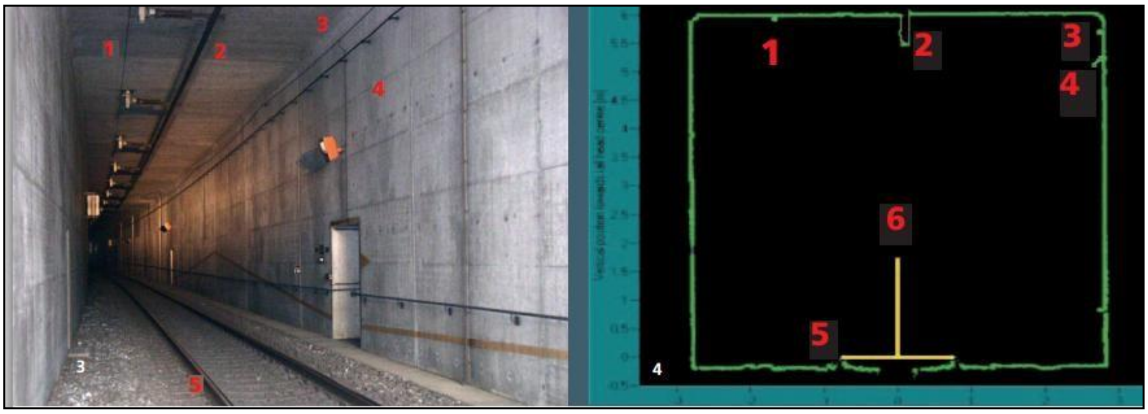
3.7.4. Train Positioning in Railway Systems

Train positioning is an important requirement in railway signaling systems, especially for latest generation of underground railway systems. Various position tracking approaches and equipment are already available for supporting the CUTP or velocity updates. The details of general train localization would be summarized in Chapter 5.2.

✓ Gives clear introductory paragraph stating main topic of section and background

3.8. Mobile Profile Scanning

The MLS can be decomposed and implemented for railway profile scanning using the center line of rail track as localized reference (Yoon et al., 2009, "Clearance Profile Scanner CPS," n.d.), which does not require the INS as the navigation solution. Such simplified system architecture provides real-time operation by referencing the measurement data to the track coordinate system as marked with number 6 as shown in **Figure 8** and is used for monitoring the condition of railway infrastructure.



-

Figure 8: Profile Scanner of *Fraunhofer IPM* ("Clearance Profile Scanner CPS," n.d.)

Although the profile scanning is simplified and is able to work as a real-time solution, there exists some limitations for its usage. The scanning data is locally referenced to rail track through the scanning data itself without external navigation measurement. However, the orientation of scanning is limited in vertical direction to minimize the uncertainties of displacement due to attitude variation and train motion. The simplified MLS cannot scan the front or rear of the train for other purposes, such as detection of non-permanent objects or dynamic monitoring of train separation. Moreover, the scanning data is still subject to uncertain position errors along the navigation direction, depending on the availability of navigation information.

✓ Gives evaluative comments outlining limitations

Refer to the source of these comments, i.e. "These studies also report..."

3.9. Simultaneous Localization and Mapping

The ***Simultaneous Localization and Mapping*** (SLAM) is a technique typically adopted for robotic or autonomous vehicle systems to simultaneously map the environment and position (localize) itself within the map. It is a traditional concept in computer science and can be implemented by flexible components and computation approaches. It can applied for processing the Mobile Laser Scanning data and had been studied (Elseberg et al., 2012; Suzuki et al., 2010). More details are presented in Chapter 5.4.

✓ Directs the reader to later chapter, and uses present simple tense, i.e. "is summarised".

-

4. Potential Development and Applications

Finite research has been conducted for operating MLS systems in total GNSS-free environment or railway environment. However, the applications of MLS technique are still post-processing and adjustment. Once the fundamental shortcomings of MLS are solved, the stability and reliability of measurement can be enhanced for further applications. It is believed that the development of URLS can be significantly valuable to establish various potential development and applications in underground railways.

Avoid vague phrases, e.g. "finite", a better alternative is "limited".
✓ Uses present perfect tense to discuss recent

Mention the applications that are discussed in the introductory paragraph, i.e. "valuable for monitoring, safety, and automation".

4.1. Real-Time or Near Real-Time Monitoring

The URLS might be capable of real-time measurements for any train, such that continuous tunnel monitoring can be conducted. The point cloud data can be transmitted to OCC or stored in train-borne computer system for self-analysis.

In addition to existing monitoring systems, the URLS can open up an integrated solution for mapping and monitoring most of the underground infrastructure by single measurement system, such as tunnel structure, rail track, overhead cable, point machine, wayside equipment etc. It might be possible to replace part of the monitoring systems, while it can integrate and visualize different monitoring results. Moreover, URLS can provide a dynamic solution for improving the availability and the flexibility of railway monitoring.

Use articles when describing individual systems, i.e. "a train-borne computer system" and "a single measurement system".

-

4.2. Train-borne Hazard Detection

Research in train-borne obstacle detection has been conducted, while the URLS solution might be a more comprehensive approach designed for multi-purposes. Obstacle or train detection is also the functions for an URLS solution, while the condition of railway tunnel can be monitored by any train equipped with URLS at the same moment. The risk of collision to trackside objects or equipment damages can be further minimized. The advancement of solution might provide an alternative to achieve a higher level of service reliability and safety through risk management and hazard detection.

4.3. Train Localization

The methods for train localization are critical issues for safety and train regulation for railway system. Traditional methods usually rely on trackside equipment, such as location beacon, track circuits, or inductive loops, which costs high amount of installation and maintenance fee (Sin, 2013a). Modern signaling system requires dynamic train positioning to facilitate the efficiency with moving block signaling control. It can be implemented by train-borne localization methods or train detection with loops. The uncertainty of train-borne localization has to be re-initialized through calibration beacon.

> Define and explain key terms when first introduced, i.e. "Train Localization, which is…"

> Make sure that it is clear what pronouns such as "it" refer to.

A real-time URLS solution can support the train localization by its measurements, which is especially helpful if the railway communication system is down and aid the train to localize itself for system initialization. The safety enforcement by URLS can provide external train detection to prevent rear-end collision under degraded mode of operation.

-

4.4. Train Control Automation

The train control and signaling system is a vital and key component to modern railway systems, which provides the fundamental signaling, control and protection to trains and interface to the supervision of train network for safety and efficiency. ***Advanced Train Control System*** (ATCS), ***Chinese Train Control System*** (CTCS) or ***European Train Control System*** (ETCS) are the examples of national standards designed to unify the safety systems for railways. The standards are usually specified at different levels according to the integrity of train control and supervision.

Do not use bolded font when introducing names of a system.

For underground railways, the degree of automation is a critical issue to railway operation, since the safety, capacity and stability has to be maximized by rigorous train control and supervision.

The specification of train control and signaling systems requires measures to perform safety enforcement for train operation, such as supervising guideway to prevent collision with obstacles, or persons on tracks as shown in **Figure 9** (Sin, 2013b).

Basic functions of train operation		On-sight train operation	Non-automated train operation	Semi automated train operation	Driverless train operation	Unattended train operation
		GOA0	GOA1	GOA2	GOA3	GOA4
Ensure safe movement of trains	Ensure safe route	x (points command/control in system)	system	system	system	system
	Ensure safe separation of trains	x	system	system	system	system
	Ensure safe speed	x	x (partly supervised by system)	system	system	system
Drive train	Control acceleration and braking	x	x	system	system	system
Supervise guideway	Prevent collision with obstacles	x	x	x	system	system
	Prevent collision with persons on tracks	x	x	x	system	system
Supervise passenger transfer	Control passengers doors	x	x	x	x	system
	Prevent injuries to persons between cars or between platform and train	x	x	x	x	system
	Ensure safe starting conditions	x	x	x	x	system
Operate a train	Set in/set off operation	x	x	x	x	system
	Supervise the status of the train	x	x	x	x	system
Ensure detection and management of emergency situations	Perform train diagnostic, detect fire/smoke and detect derailment, detect loss of train integrity, handle emergency situations (call/evacuation, supervision)	x	x	x	x	system and/or staff in OCC
NOTE x = responsibility of operations staff (may be realised by UGTMS system) System = shall be realised by UGTMS system						

-

Figure 9: Grade of Automation (Sin, 2013b)

URLS can provide an alternative method for automatic detection and identification of obstacles, which is possible to support driverless train operation or unattended train operation.

✓ Gives short summary of section

5. Work to Date

Work that has been conducted and relevant topics studied for this research and are summarized in this chapter. The Hong Kong MTR underground railway has been selected for the sample for study. Since the MTR adopted proven technology and existing systems with international standards, it can represent most of the modern railway systems. Such that the expedients and limitations are more realistic and are considered for evaluating the various solutions.

✓ Gives clear introductory sentence outlining chapter

Do not overuse "can". If something is true it is not needed, i.e. rather than "it can represent..." better "it represents..."

5.1. Track Alignment for Railway System

In railway environment, the definition of track alignment is one of the most critical information for precise localization, which serves for geo-reference of alignment. In order to utilize the track alignment for navigation solution, a set of alignment data (Section of Tseung Kwan O Extension 2002) was obtained from the MTRC for preliminary study.

Verification of alignment computation and data extraction had been conducted through simulation test, while the result matches with graphical record. However, physical errors such as the variation between the rail track and alignment data might be critical.

Have a new paragraph for each idea, i.e.

1. Data collection
2. Limitations of data collection

-

5.1.1. <u>Track Alignment Data</u>

The MTRC defines the track alignment by its centre line geometry, which follows the conventional approach and is decomposed into horizontal alignment and vertical alignment. The track alignment data is stored as digital CAD files. Geometry data can be exported from the files in either graphical or numerical format.

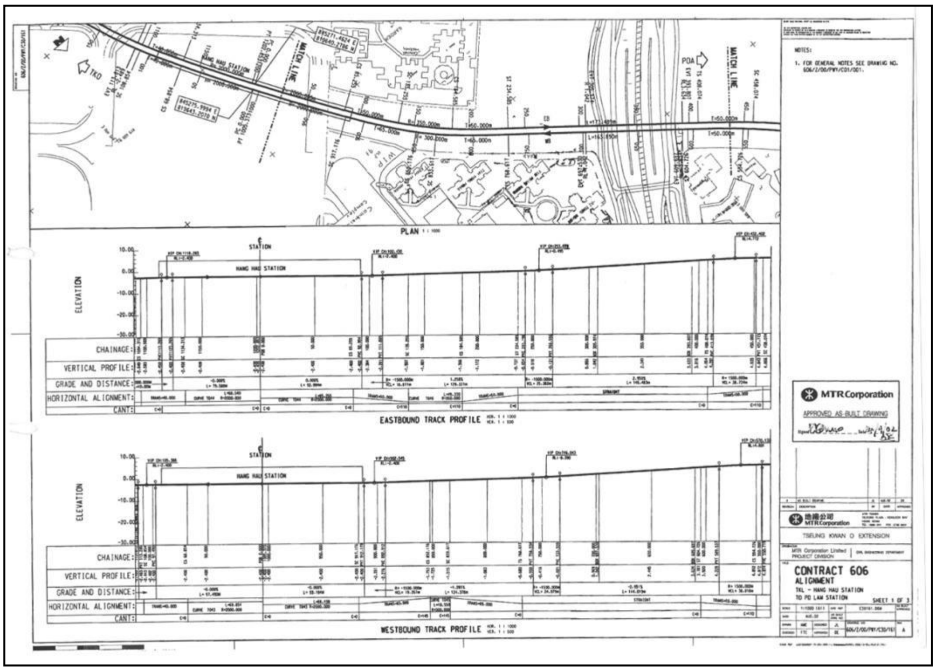


Figure 10: CAD Drawing for Sample Alignment Data

Figure 10 shows the CAD drawing format of alignment data. It consists of a 2-dimensional plan for the alignment. More details and parameters are shown with track profile and referenced to alignment chainage. **Figure 11** shows the numeric format of horizontal alignment data, which is exported result from CAD file and describes the necessary parameters for defining horizontal alignment.

-

POINT TYPE	STATION	EAST(X)	NORTH(Y)	BEARING	RADIUS	ELE_LENGTH
PC	0.000	845271.39753	819640.37932	327^12'52.312"		
CC		843589.98961	818557.38930		-2000.000	85.255
CS	85.255	845223.71917	819711.04770	324^46'19.800"		
CS	85.255	845223.71917	819711.04770	324^46'19.800"		
SC	135.255	845193.58920	819750.93090	319^57'48.290"		50.000
SC	135.255	845193.58920	819750.93090	319^57'48.290"		
CC		844925.61736	819525.78407		-350.000	49.330
CS	184.585	845159.30397	819786.34226	311^53'16.630"		
CS	184.585	845159.30397	819786.34226	311^53'16.630"		
ST	234.585	845120.54322	819817.90918	307^47'43.430"		50.000

Figure 11: Geometry Report for Horizontal Alignment

5.1.2. Definition of Horizontal Alignment

✓ Gives clear definition of horizontal alignment and vertical alignment in 5.1.2 and 5.1.3

The horizontal alignment of rail track centre line is defined between stations or described by sections for two or three stations. The sections are generally classified into straight line, circular curve and spiral curve by different point types as shown in **Figure 11** and are sequentially defined with stations. To facilitate the alignment computation, the geometry data is generalized into a format defined at the start of section.

Type,	Station,	Easting,	Northing,	TangentBrg,	Radius1,	Radius2,	Length,	Cant
03,	0.000,	845271.39753,	819640.37932,	327.1252312,	-2000.000,	-2000.000,	85.255,	0.000
05,	85.255,	845223.71917,	819711.04770,	324.4619800,	-2000.000,	-350.000,	50.000,	0.000
03,	135.255,	845193.58920,	819750.93090,	319.5748290,	-350.000,	-350.000,	49.330,	0.110
04,	184.585,	845159.30397,	819786.34226,	311.5316630,	-350.000,	+0.000,	50.000,	0.000
01,	234.585,	845120.54320,	819817.90920,	307.4743431,	+0.000,	+0.000,	173.489,	0.000
02,	408.074,	844983.45145,	819924.23083,	307.4743431,	+0.000,	+500.000,	50.000,	0.000
03,	458.074,	844944.46172,	819955.52373,	310.3936672,	+500.000,	+500.000,	93.330,	0.110
04,	551.403,	844879.73252,	820022.57053,	321.2117875,	+500.000,	+0.000,	50.000,	0.000
01,	601.403,	844849.82999,	820062.63652,	324.1311115,	+0.000,	+0.000,	45.975,	0.000
02,	647.378,	844822.94935,	820099.93454,	324.1311115,	+0.000,	+650.000,	30.000,	0.000
03,	677.378,	844805.59715,	820124.40612,	325.3231072,	+650.000,	+650.000,	25.591,	0.060
04,	702.969,	844791.53690,	820145.78628,	327.4751795,	+650.000,	+0.000,	30.000,	0.000
01,	732.969,	844775.94239,	820171.41378,	329.0711752,	+0.000,	+0.000,	26.821,	0.000
03,	759.791,	844762.17648,	820194.43311,	329.0711752,	-561.344,	-561.344,	48.009,	0.060

Figure 12: Generalized Format for Horizontal Alignment

In **Figure 12**, the sections are coded with 2-digit number: 01 for straight line, 02 for spiral curve, 03 for circular curve, 04 for reverse spiral curve, and 05 for transition spiral. All the necessary parameters are reduced for each section.

-

In addition to the general definition of horizontal alignment, cant is another parameter extracted for track data. It is the elevation difference between inner rail and outer rail, which is defined with the radius of curvature. It functions as superelevation to provide additional centripetal force for a rail-bounded vehicle to turn at a curve and is applied to distribute the loading across both sides of wheels, minimize the lateral forces by gravity, allow a higher speed at curve and maintain passenger comfort.

5.1.3. Definition of Vertical Alignment

The vertical alignment is defined between stations that are different from horizontal stations, while both of them are referenced to the same system of alignment chainage. It can also be divided into sections with constant geometric features. The sections are classified as vertical circular curve and straight line.

POINT TYPE	STATION	LEVEL	GRADE	RADIUS	ELE_LENGTH
POB	0.000	-2.400	0.00000		
PVC	92.994	-2.400	0.00000		92.994
PVI	102.430	-2.400		-1500.000	18.871
PVT	111.865	-2.281	0.01258		
PVC	223.435	-0.878	0.01258		111.570
PVI	236.120	-0.718		-1500.000	25.365
PVT	248.800	-0.344	0.02950		
PVC	409.310	4.392	0.02950		160.509
PVI	429.251	4.980		1500.000	39.891
PVT	449.201	5.038	0.00290		
PVC	632.365	5.568	0.00290		183.164
PVI	641.633	5.595		-2000.000	18.535
PVT	650.900	5.708	0.01216		
POE	807.847	7.617	0.01216		156.947

-

Figure 13: Generalized Format for Horizontal Alignment

The vertical alignment is geo-referenced with level at each station reduced to the ***Hong Kong Principal Datum*** (HKPD). It is defined by gradient of vertical curvature and radius of vertical curvature. For computation convenience, the geometry data is generalized into a format defined at starting of section as shown in **Figure 14**.

✓ uses wide range of passive structures to define and explain, e.g. "is defined", "are referenced" "can also be divided" "are classified as" "is generalized into"

Station ,	Level,	GradIn,	GradOut,	Length
0.000,	-2.400,	0.00000,	0.00000,	92.994
92.994,	-2.400,	0.00000,	0.01258,	18.871
111.865,	-2.281,	0.01258,	0.01258,	111.570
223.435,	-0.878,	0.01258,	0.02950,	25.365
248.800,	-0.344,	0.02950,	0.02950,	160.510
409.310,	4.392,	0.02950,	0.00290,	39.891
449.201,	5.038,	0.00290,	0.00290,	183.164
632.365,	5.568,	0.00290,	0.01216,	18.535
650.900,	5.708,	0.01216,	0.01216,	156.947
807.847,	7.617,	0.01216,	0.00000,	0.000

Figure 14: Generalized Format for Vertical Alignment

5.1.4. Reduction for Horizontal Alignment

The simplest type of horizontal alignment is a straight line section. The position of a point is defined by horizontal chainage difference from a reference point towards a direction. Hence, the coordinates of an arbitrary point ***i*** can be computed through a general 2-dimensional transformation:

Equation 11

$$\begin{bmatrix} E_i \\ N_i \\ \alpha_i \end{bmatrix} = \begin{bmatrix} E_0 + y_i \cos\alpha_0 + x_i \sin\alpha_0 \\ N_0 - y_i \sin\alpha_0 + x_i \cos\alpha_0 \\ \alpha_0 + \phi_i \end{bmatrix}$$

where

-

E_i, N_i and E_0, N_0 are the coordinates of an arbitrary point *i* and reference point respectively; α_i and α_0 are the tangent bearing of alignment at point *i* and reference point respectively; x_i is the horizontal chainage difference from reference point to an arbitrary point *i*; y_i is the offset to the alignment tangent direction; ϕ_i is the deflection angle which is zero for straight alignment.

✓States equations and describes them using mathematical language

The general transformation model is not limited to straight line sections but also for sections with curvature. For circular curve section, the geometry is defined by an additional deflection angle, which can be determined from central angle: **Equation 12**

$$\phi_i = \frac{L_i}{R}$$

where ϕ_i is the deflection angle from tangent bearing; L_i is the relative chainage; R is the radius of curvature.

The circular curve can be defined in a local coordinate system as shown in **Figure 15**. The coordinates of arbitrary point *i* with respect to local coordinate system can be defined with the deflection angle:

Equation 13

$$\begin{bmatrix} x_i \\ y_i \\ \phi_i \end{bmatrix} = \begin{bmatrix} 2R\sin\frac{\phi_i}{2}\cos\frac{\phi_i}{2} \\ 2R\left(\sin\frac{\phi_i}{2}\right)^2 \\ \frac{L_i}{R} \end{bmatrix} = \begin{bmatrix} R\sin\frac{L_i}{R} \\ R - R\cos\frac{L_i}{R} \\ \frac{L_i}{R} \end{bmatrix}$$

-

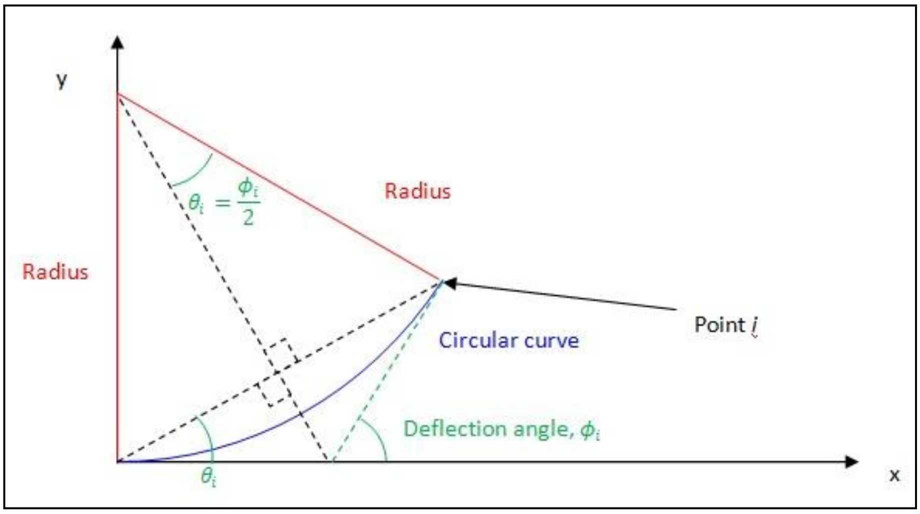


Figure 15: Localized Definition of Circular Curve

The localized coordinates can be transformed into reference coordinate system through the general transformation model developed in **Equation 11**.

Refer to figures in text.

In addition to the circular curve, spiral curve serves for the connection between sections with different radii of curvature. In railway environment, spiral curve is usually defined by Clothoid, which is expressed as changing curvature with respect to radius and curve length:

Equation 14

$$\frac{1}{k^2} = R_i L_i = RL$$

where k is the curvature for alignment design; R_i and R are the radii of curvature at point i and design circular curve respectively; L_i is the curve length from reference point to point i; L is the total length of curve section.

-

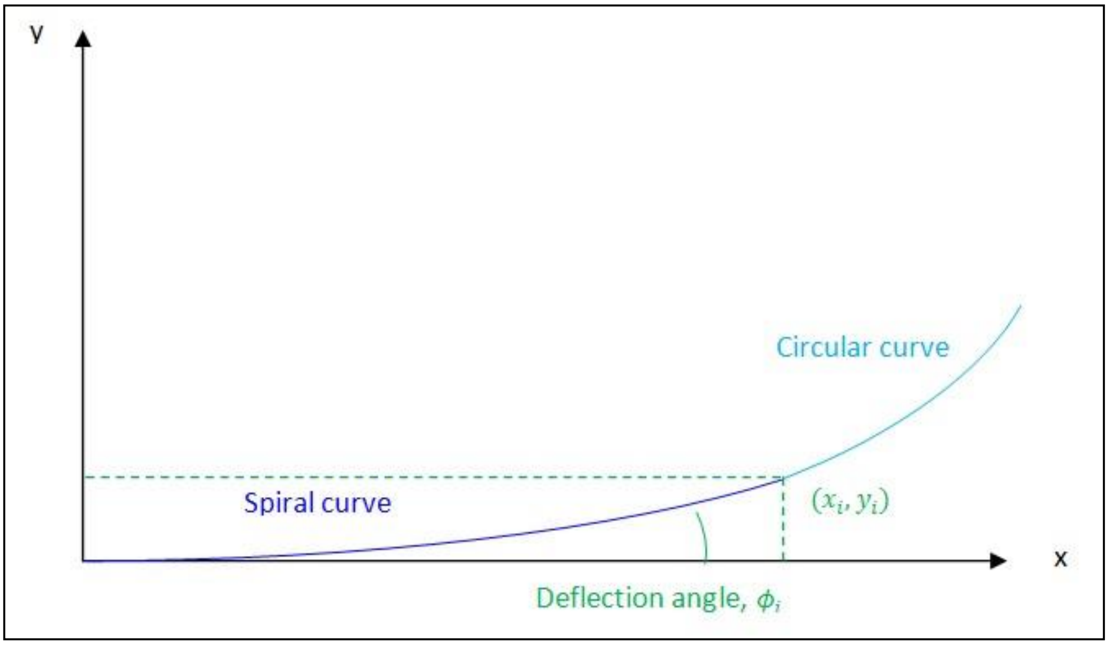


Figure 16: Localized Definition of Spiral Curve

The position of point i along the spiral section is determined with curve length L_i from a reference point. **Figure 16** shows the definition of a simple spiral curve within a local coordinate system. The fundamental of clothoid spiral is defined with the deflection angle of curvature:

✓ Refers to figure and explains main features

Equation 15

$$\phi_i = \frac{{L_i}^2}{2RL}$$

Through the integration of cosine and sine functions of the deflection angle, the relative coordinates of point i can be determined:

-

Equation 16

$$\begin{bmatrix} x_i \\ y_i \\ \phi_i \end{bmatrix} = \begin{bmatrix} L_i - \frac{{L_i}^5}{40R^2L^2} + \frac{{L_i}^9}{3456R^4L^4} - \frac{{L_i}^{13}}{599040R^6L^6} + \cdots \\ \frac{{L_i}^3}{6RL} - \frac{{L_i}^7}{336R^3L^3} + \frac{{L_i}^{11}}{42240R^5L^5} - \cdots \\ \frac{{L_i}^2}{2RL} \end{bmatrix}$$

The localized coordinates can be transformed into reference coordinate system through the general transformation model developed in **Equation 11**.

In addition to the reduction of horizontal alignment, the cant parameter for superelevation can be calculated from the constant cant values in circular curve sections, which is done by a transformation through a cosine function with proportion of relative chainage:

Equation 17

$$c_i = c_1 + \frac{(c_2 - c_1)}{2}\left[1 - \cos\left(\frac{\pi L_i}{L}\right)\right]$$

where c_i is the cant at point i; c_1 and c_2 are the constant cant values a previous and following sections.

The horizontal position of rail track can be estimated from the alignment centre line offset with width of track and cant rotation:

Equation 18

$$d_{offset} = \frac{d_{width}}{2}\cos\left[\sin^{-1}\left(\frac{c_i}{d_{width}}\right)\right]$$

where

d_{width} is the width of rail track;

d_{offset} is the horizontal offset of rail track from centre line.

-

5.1.5. *Reduction for Vertical Alignment*

The vertical curve can be described by a parabolic function (2nd order polynomial), which is a general expression for both vertical curve and straight line sections. The level of point i can be determined from chainage:

Equation 19

$$y = a_0 x^2 + a_1 x + a_2$$

where *y* is the level of point i; *x* is the chainage of point i; a_i is the polynomial coefficient for *i* = 0, 1, 2.

From the parabolic equation, the three polynomial coefficients can be formulated from the parameters.

Equation 20

$$y|_{x=0} = a_2 = h_1$$

$$\left.\frac{dy}{dx}\right|_{x=0} = a_1 = g_1$$

$$\frac{d^2y}{dx^2} = 2a_0 = g_2 - g_1$$

$$\therefore a_0 = \frac{g_2 - g_1}{2}$$

where

h_1 is the level of station; g_1 and g_2 are the gradients of station and the bounding station.

With the polynomial defined for vertical curvature, the gradient of point i can be determined from its derivative:

-

Equation 21

$$g_i = 2a_0 2 + a_1$$

5.1.6. Checking for 3-dimensional Alignment Data

The computation is implemented for the sample data. A set of navigation distance is assumed to be measurement output from external sources. The navigation distance is the accumulation of length in 3-dimensional space, which has to be reduced to horizontal distance. Therefore, the set of data can be simulated from the arc-length of vertical parabolic curve through integration:

Avoid extra propositions, they sometimes change meaning. i.e. "check up", "check in" "check for" are all different from "check". The subtitle is better as "Checking 3-dimensional Alignment Data".

Equation 22

$$L_c = \int_0^{L_i} \sqrt{1 + (2a_0 x + a_1)^2}\, dx$$

where *a* and *b* are location along *x*, correspond to horizontal chainage; L_c is the cumulative distance.

The integration represented in **Equation 22** can be done by substitution. Let $t = 2a_0 x + a_1$, such that:

Equation 23

$$L_c = \frac{1}{2a_0}\int_{a_1}^{2a_0 L_i + a_1} \sqrt{1 + t^2}\, dt = \frac{1}{2a_0}\left|\frac{t}{2}\sqrt{1 + t^2} + \frac{1}{2} sinh^{-1}\, t\right|_{a_1}^{2a_0 L_i + a_1}$$

where

$dt = 2a_0\, dx$ is substituted into equation.

If the gradient is constant, $a_0 = 0$ and the cumulative distance from **Equation 23** is undetermined. Therefore, the cumulative distance can be alternatively estimated:

-

Equation 24

$$L_c = \sqrt{a_1^2 L_i^2 + L_i^2}$$

Since the navigation distance is simulated from horizontal chainage, a correction model can be estimated with a 3rd order polynomial for the difference between L_i and L_c, such that the correction from navigation distance to horizontal chainage can be estimated.

Equation 25

$$y = b_0 x^3 + b_1 x^2 + b_2 x + b_3$$

where y is correction for cumulative distance x;

b_0, b_1 ,b_2 and b_3 are the polynomial coefficients and $b_3 = 0$.

The simulated data is used for estimating the polynomial coefficients through least squares approach, because the data is not perfectly defined analytically. Consequently, the correction can be estimated and applied as:

Equation 26

$$\hat{L}_i = L_c + \Delta L = L_c + b_0 {L_c}^3 + b_1 {L_c}^2 + b_2 L_c$$

where $\hat{L}_i$ is the estimated horizontal chainage of point i.

Using the simulated set of cumulative navigation distance, alignment information such as position, tangent bearing, cant, gradient and radius of curvature can be reduced as shown in **Figure 17**.

-

Chainage	Easting	Northing	Level	Cant	Gradient	Bearing	RDist	Radius
0.000	845271.39753	819640.37932	-2.40000	0.00000	0.00000	327.1252312	0.00000	-2000.00000
5.000	845268.68480	819644.57945	-2.40000	0.00000	0.00000	327.0416650	5.00000	-2000.00000
10.000	845265.96158	819648.77279	-2.40000	0.00000	0.00000	326.5540988	10.00000	-2000.00000
15.000	845263.22789	819652.95930	-2.40000	0.00000	0.00000	326.4705326	15.00000	-2000.00000
20.000	845260.48374	819657.13897	-2.40000	0.00000	0.00000	326.3829664	20.00000	-2000.00000
25.000	845257.72915	819661.31176	-2.40000	0.00000	0.00000	326.2954002	25.00000	-2000.00000
30.000	845254.96413	819665.47766	-2.40000	0.00000	0.00000	326.2118340	30.00000	-2000.00000
35.000	845252.18871	819669.63663	-2.40000	0.00000	0.00000	326.1242678	35.00000	-2000.00000
40.000	845249.40290	819673.78865	-2.40000	0.00000	0.00000	326.0407016	40.00000	-2000.00000
45.000	845246.60672	819677.93369	-2.40000	0.00000	0.00000	325.5531354	45.00000	-2000.00000
50.000	845243.80019	819682.07172	-2.40000	0.00000	0.00000	325.4655692	50.00000	-2000.00000
55.000	845240.98332	819686.20273	-2.40000	0.00000	0.00000	325.3820030	55.00000	-2000.00000
60.000	845238.15613	819690.32668	-2.40000	0.00000	0.00000	325.2944368	60.00000	-2000.00000
65.000	845235.31863	819694.44355	-2.40000	0.00000	0.00000	325.2108706	65.00000	-2000.00000
70.000	845232.47086	819698.55332	-2.40000	0.00000	0.00000	325.1233044	70.00000	-2000.00000
75.000	845229.61282	819702.65595	-2.40000	0.00000	0.00000	325.0357382	75.00000	-2000.00000
80.000	845226.74453	819706.75143	-2.40000	0.00000	0.00000	324.5521720	80.00000	-2000.00000
85.000	845223.86602	819710.83972	-2.40000	0.00000	0.00000	324.4646058	85.00000	-2000.00000
90.000	845220.97684	819714.91999	-2.40000	0.00243	0.00000	324.3620970	90.00000	-1381.80167
94.999	845218.07307	819718.98956	-2.39866	0.00999	0.00134	324.2153191	95.00000	-1042.34466
99.992	845215.15381	819723.03965	-2.38368	0.02194	0.00466	324.0324056	100.00000	-837.00378
104.976	845212.21530	819727.06563	-2.35214	0.03709	0.00799	323.4054970	105.00000	-699.44110
109.952	845209.25305	819731.06407	-2.30414	0.05395	0.01130	323.1427096	110.00000	-600.85127

Figure 17: Reduction for Simulated Data

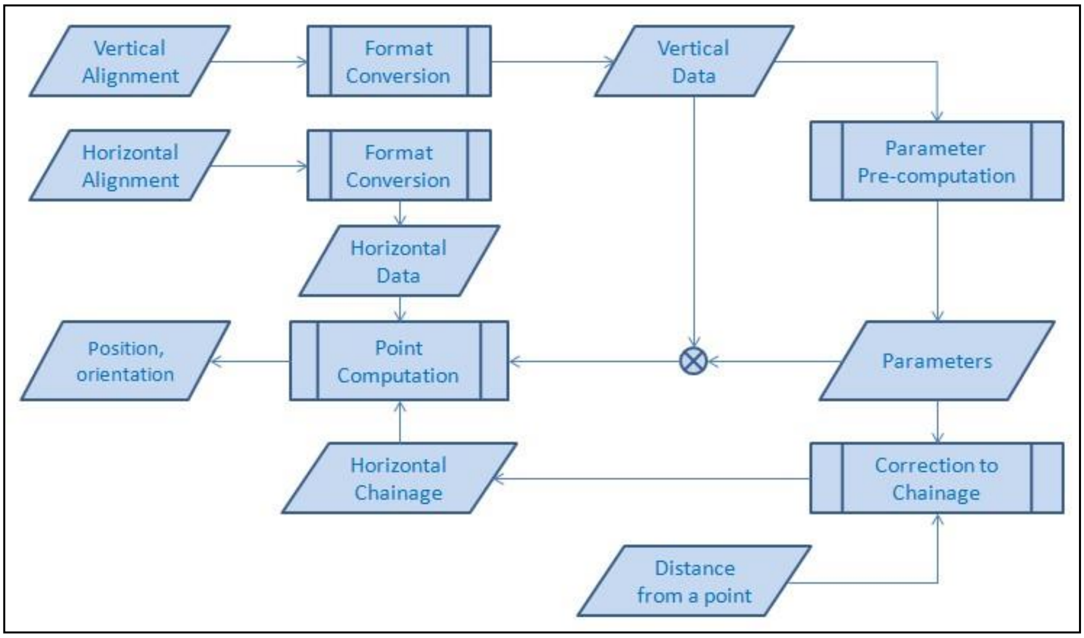


Figure 18: Flow Chart for Simulation Test

-

The reduction from track alignment can provide additional information besides the 3-dimensional coordinates of a single point, such as the cant, gradient, tangent bearing and radius of curvature. The alignment chainage can also be the position reference to store external source of constant information as mentioned in previous chapter.

✓Refers back to previous discussion

Avoid "mentioned". Use "As discussed in chapter 3.

5.2. Studies in Railway Systems

The fundamentals of railway system are being studied through a course for Signaling and Train Control System. The train localization is a main issue for safety operation in railway signaling system, especially for railway systems developing towards ***Communication Based Train Control*** (CBTC). By understanding the train localization techniques, it has been found that various existing devices are available for railway systems. Although there are still critical drawbacks in their positioning performance, the integration of MLS and train localization is still a potential solution.

5.2.1. Communication Based Train Control

Understanding the train control and signaling system is important for realizing the advantages or limitations of possible MLS implementation. The trend of underground railway systems is being developed towards automation. The concept of ***Communication Based Train Control*** (CBTC) system is specified for GoA4 and defined in IEEE 1474.1 (Sin, 2013b). It has evolved from traditional ***Automatic Train Control*** (ATC) system, which utilizes the moving block signaling system for railway management to assure the maximum level of system performance and flexibility. The train control is implemented through continuous, bi-directional radio frequency

Have a clear topic sentence explaining the main point of the paragraph and to link all the sentences to the main point.

State directly what work has been done on the project relating to this.

-

communication between train and trackside to permit the transfer of more control and status data.

The train location for CBTC system has to be determined with high precision and independent to conventional trackside detection methods, such as track circuit and axle counter. Train location is continuously updated to the control system for train regulation. Hence, the headway can be further minimized with the assuring safety distance between trains.

The data communication within CBTC system is flexible and computerized. Information, such as routing of train, speed regulation (acceleration/deceleration) and self localization, can be by-passed to the operation control for aiding the MLS. For future development of URLS solution, it might support the CBTC in real-time operation.

Avoid vague sentences such as "it might support the…" State "It is expected that…"

5.2.2. Trackside Detection Methods

For ordinary railway systems with less demand of efficiency, discrete train detection can meet the safety requirements. General methods, such as wheel detector, treadle, track circuit or axle counter, can be implemented through trackside equipment.

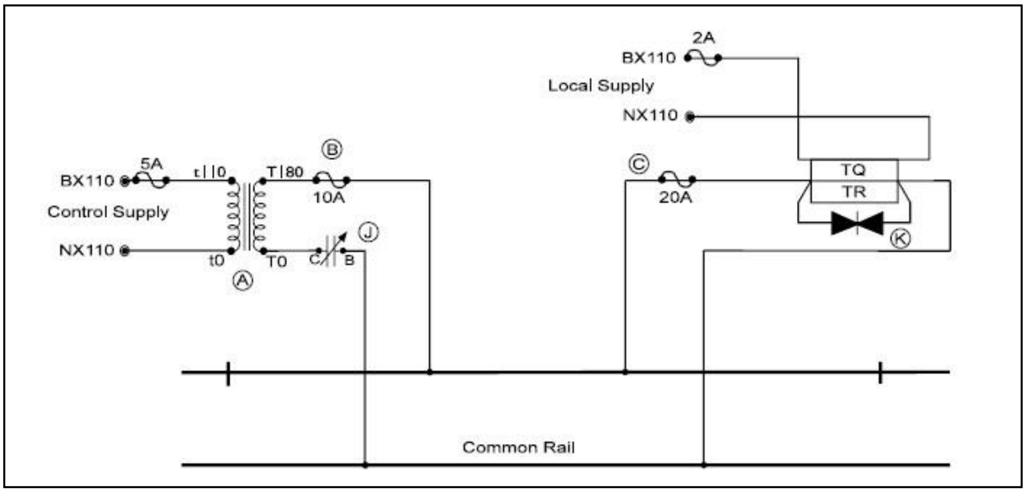


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Figure 19: Configuration of Single Rail AC Track Circuit (Sin, 2013a)

The track circuit method can be traced back to 1870s, which is the most common device for train detection in railway worldwide (Sin, 2013a). General track circuit can be classified into four types: DC track circuit, AC track circuit, audio frequency track circuit, and high voltage impulse track circuit, which have similar functions to detect the existence of train and interlock with signaling control. **Figure 19** shows the configuration of AC track circuit.

Do not repeat background information in this section, it is better to include it earlier in the Literature Review.

Figure 20: Axle Counter Installation (Left) and Detector Head (Right) (Sin, 2013a)

Figure 20 illustrates the installation of axle counter and its detect head. The axle counters are installed at distance and detect the existence of train in pairs. A region is enclosed by two axle counter units, which is clear for occupation only if the counting of number of axle in and out are the same. However, it is not fail-safety design and usually serves as back-up solution for malfunction of other methods.

✓ Explains how methods are used
✓ Critically evaluates systems starting with "However…"

The trackside detection methods can support a fixed block architecture for railway signaling system. However, the efficiency of train signaling is limited by the block occupation. The positioning resolution is too low for supporting the MLS navigation, while the detection is not

-

train-borne. Significant advantage of trackside detection devices is that they can act as physical objects to be mapped at fixed locations.

Nowadays, moving block architecture is more common for enhancing the operation through semi-continuous or continuous train localization, which are implemented through various types of measurement sensors. The velocity measurement or train localization information is more possible to support the MLS for positioning.

> Do not use "possible" to refer to ability, it refers to chance, better is ""is more able to..."

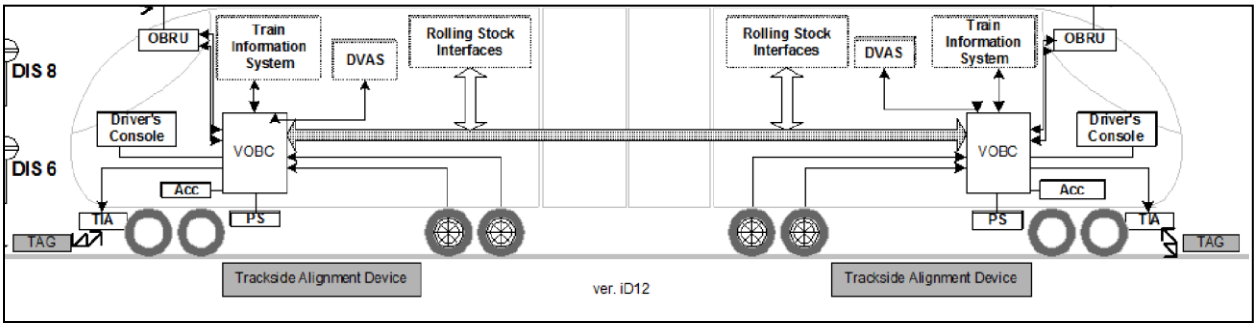

Figure 21: Typical Train-borne Architecture (Sin, 2011)

Figure 21 illustrates a typical train-borne architecture, which consists of various devices for transmission of signal and measurement for train localization. The self localization information is more suitable for supporting MLS navigation.

5.2.3. Tachometer

Tachometer is usually a device for counting the resolution of wheels, such that the navigation distance or velocity can be estimated with wheel's diameter and angular rate. For rail guided applications, different types of analogue or digital tachometers have been used, such as capacitative, active and passive electromagnetic tachometers (Mirabadi et al., 1996). Absolute optical and incremental optical

> ✓ Introduces concept generally
> ✓ Discusses how it specifically relates to railways
> ✓ Gives references
> Better to use "become" when discussing changes, i.e. "trachometers are becoming available."

-

tachometers are being available to provide more accurate and efficient velocity control.

Figure 22: Tachometer Installed to Train Wheel (Sin, 2013a)

Figure 22 shows the tachometer installed to a train. It is the fundamental device installed to all trains because of low instrumental cost. The drawbacks are low measurement resolution; long sampling time; large electrical noise; mechanical imperfection; position error accumulation.

✓ States strengths and weaknesses

5.2.4. Transponder

Transponder can be passive or active device, which is installed to trackside for one-way or two-way intermittent communication with the train. It can be used to transmit a signal including information on the sensor, position, speed limit or signaling information to the train-borne receiver.

✓ Explains key system

Place this in the earlier chapter that reviews systems and concepts.

The position of train can be determined by track-to-train communication through the transponders. It is a non-continuous approach for train localization, which is usually integrated with other positioning methods to serve for the requirements of moving block signaling architecture. Accuracy of 15 cm can be achieved with the use of Doppler RADAR (Becker et

-

al., 2006), while standalone positioning accuracy can be as low as 5 m in longitudinal direction (Hartwig et al., 2006).

5.2.5. *Eddy-Current Sensor*

Eddy-current sensor can be used for measuring displacement. High-performance sensors can provide linear measurement which is stable with temperature, and able to resolve incredibly small changes in target position resulting in high resolution measurements. It can be applied to train positioning with reliable, slip-free velocity and distance measurements along the rail track. From the analysis of signal, switches and position of points can be detected for resetting absolute location without additional infrastructure for the rail track (Geistler, 2002).

> Use articles and plurals with key words that are countable nuns, i.e. "Eddy-current sensors"
> "provide a linear measurement",
> "the reference source".

5.2.6. *Doppler Measurement*

The speed of the train can be estimated by Doppler measurement with LiDAR or RADAR (Wrobel, 2013). It measures the frequency changes of reference source of waveform due to the speed (Mirabadi and Mort, 1996):

Equation 27

$$\Delta f = \frac{2v\cos\gamma}{\lambda}$$

-

where Δf is the frequency shift of Doppler effect; v is the train speed relative to the ground; γ is the angle of radiation;

λ is the transmitted carrier wavelength.

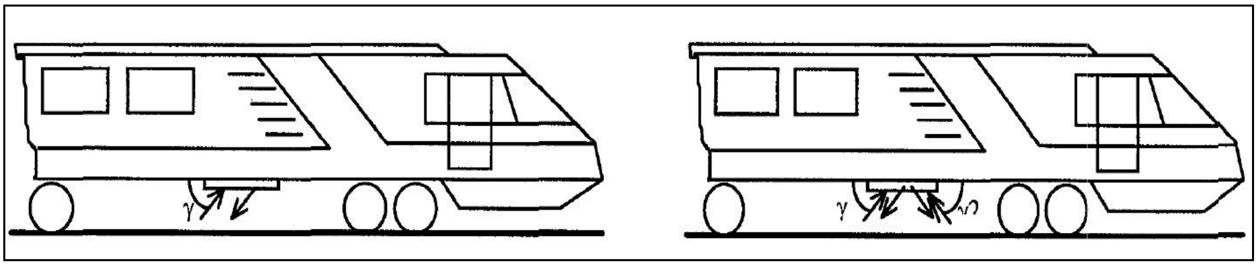

Figure 23: Configuration of Doppler Measurement Device (Mirabadi and Mort, 1996)

The Doppler RADAR can achieve higher accuracy at high speed, but produce more errors at low speed (Lv, 2010). Accuracy of 0.2% drift can be achieved (Becker et al., 2006). The specification for velocity accuracy of Doppler measurement can be described with a constant component and a scale component proportional to velocity, such as $0.5kmh^{-1} + 0.008v$ (Gerlach and Rahmig, 2009).

5.2.7. Sensor Fusion for Velocity Measurement

Different sensors can be applicable for velocity measurement with different level of precision. The fusion of sensor can be done by simple averaging/ weighted averaging, consensus sensing, or Kalman filtering (Mirabadi and Mort, 1996).

For simple/weighted averaging, the fusion of velocity measurement can be done as:

Equation 28

$$f(x_1, x_2, \dots, x_n) = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i}$$

-

where x_i is the velocity measurements from different sensors; w_i is the weight of each sensor.

The measurement input for Kalman filter process would be simplified as an estimated velocity, such that the external velocity measurement is pre-processed and loosely-coupled with INS. The reliability of different sources of measurement is defined by corresponding weight, which is not involved for the process of INS. The performance of this approach is limited by ignoring the properties of measurement sensors, which depends only on a pre-defined weight.

Do not use "would" when describing things which are possible. Better to use "is simplified" or "can be simplified" or "will be simplified".

For the approach of consensus sensing, the sensor measurement would be eliminated with respect to possible error, such that other sensors are used for calculation and data fusion. The redundant data is fed into a majority voter algorithm to eliminate minority.

The Kalman filter can take into account for all information and processes all available measurements with respect to the precision. It is based on the knowledge of the dynamics of the measurement devices, the statistical description of processing noises, measurement errors and dynamic model uncertainty.

✓ Lists basis of filter without using "etc."

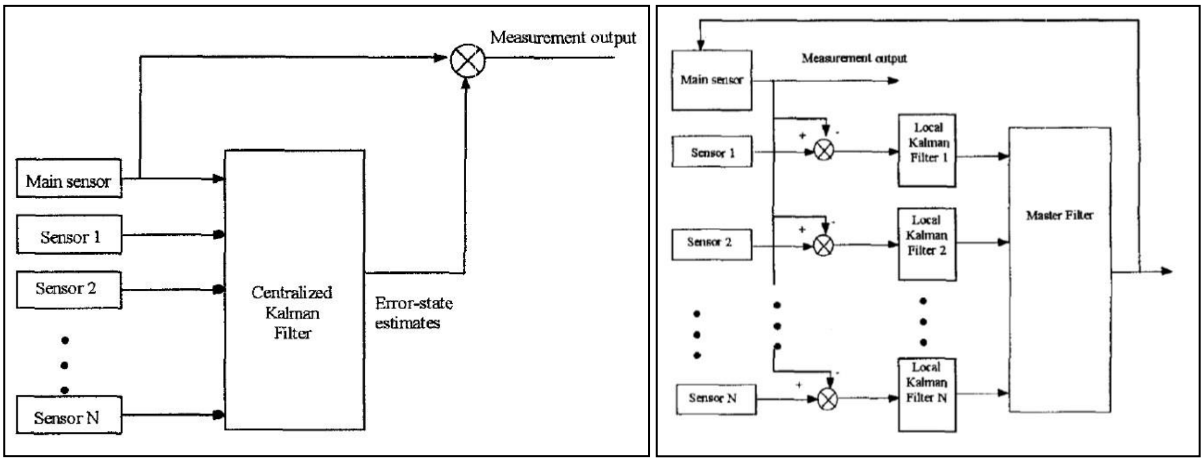

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Figure 24: Centralized Kalman Filter (Left) and Decentralized Kalman Filter (Right)

For a centralized architecture, the sensor measurements are pre-calculated and independently fed into a common Kalman filter to estimate the error state and feed back to the fundamental sensor for output.

Avoid starting each paragraph with "For…". Better to use "The sensor measurements of the centralized…" "While the main sensor measurements of the decentralized architecture…".

For a decentralized architecture, the main sensor measurements are fed into other sensors and processed with corresponding Kalman filter in parallel. The processed measurements are then processed with a common Kalman filter and fed back to the main sensor for compensation.

The sensor fusion is an important technique for external integration of various source of velocity measurements. The architecture can be simplified by loosely coupling between velocity controls and INS process through velocity update control as mentioned in Chapter 3.7. The availability of system can be enhanced by external processing of velocity measurements, which allows more flexible usage and various sources of measurements.

5.3. Fundamentals of Inertial Navigation

The inertial navigation background, processing, limitations and applications are being studied through a guided study course in navigation. The methodology for integrating Mobile Laser Scanning into underground railway system is generated with the properties and applications of inertial navigation. In this section, the fundamentals of inertial navigation are summarized.

Give more details about the course, i.e. its length, place and the organisation that is running the course

Include what has been studied to date.

-

5.3.1. Inertial Measurement Unit

Inertial Measurement Unit is the core hardware for inertial measurement consisting of group of accelerometers and gyroscopes to track the inertial linear motion and angular rotation of itself. The design of IMU platform is usually classified into two categories: Gimbaled gyro-stabilized system, and strap-down system. Nowadays, most of the general IMU are constructed with strap-down configuration.

✓ Starts with general description
✓ Gives specific details in paragraph 2.

Strap-down IMU has its inertial sensing units installed on a platform without physical compensation of platform rotations. The rotation updates are maintained through the computation of rotation matrix with gyroscope outputs. **Figure 25** shows the configuration of a strap-down IMU that both of the accelerometers and gyroscopes are linearly aligned at three orthogonal axes.

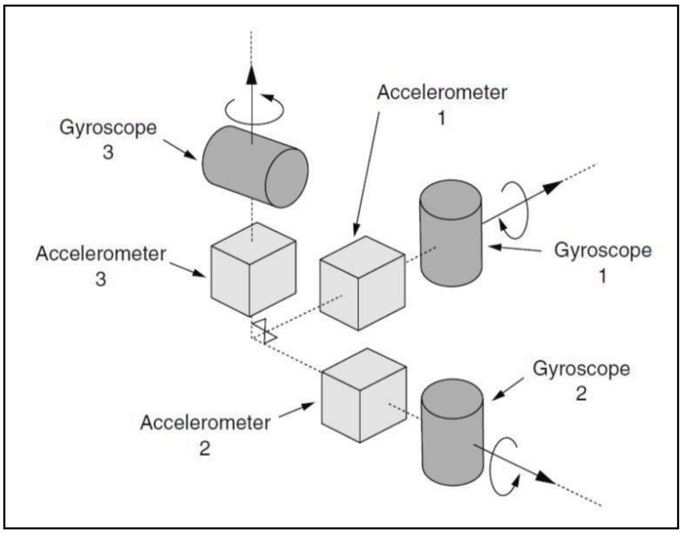

Figure 25: Configuration of Strap-down IMU (Titterton and Weston, 2004)

5.3.2. Accelerometer Unit

The principle of inertial measurement is defined with the physical property of inertia. The basic unit of accelerometer measures the change of linear motion of an object in terms of acceleration, which is quantified by force through Newton's law of motion.

-

The measurement of specific force can be implemented through the measurement of net acceleration of a physical body through the concept of spring-mass system, which is the fundamental principle of a general accelerometer. For a basic design, a spring-mass system consists of a proof mass connected to the case of accelerometer through a spring. When the accelerometer is subjected to an unbalanced net force, the motion of its case would be changed while the proof mass tends to resist the change due to its inertia.

✓ Structures subsection paragraphs clearly
paragraph 1 theory
paragraph 2 practise
paragraph 3 avalability

Various types of accelerometers are available for inertial measurement with respect to measurement range, natural frequency, measurement accuracy etc. Modern accelerometers are usually developed with similar concept of a spring-mass system, while some of the accelerometers are designed with acceleration-sensitive precession of momentum wheel gyroscope, called the gyroscopic accelerometer (Grewal et al., 2007). General accelerometers can be ***Pendulous Integrating Gyroscopic Accelerometer*** (PIGA), Piezoelectric Accelerometer, Piezoresistive Accelerometer, Capacitive Accelerometer, or MEMS Accelerometer etc.

5.3.3. Gyroscopic Unit

A general gyroscope measures the change of orientation of an object in terms of rotation rate, which is also a quantified measurement of inertia.

Rate gyroscopes are the major types of modern gyroscopes, which provides an output signal proportional to the rate of rotation or the angular velocity. There are three major types of gyroscope for angular velocity measurement, which are spinning mass gyroscope, optical gyroscope and vibratory gyroscope.

Avoid "most of the" better to use "the majority of..."

-

Most of the high performance MLS systems are equipped with optical gyroscopes, such as ***Fiber Optic Gyroscope*** (FOG) and ***Ring Laser Gyroscope*** (RLG). With the technological improvement, ***Micro Electro-Mechanical System*** (MEMS) inertial sensors are becoming more available to be the alternatives. The most significant advantages of MEMS accelerometers or gyroscopes are relatively low cost and small size, while the performance has been rapidly improved.

Use "improve" as active verb, i.e. "performance has improved"

5.3.4. Properties of Inertial Measurement Unit

The properties of inertial measurement unit are significantly important to maintain the accuracy of an INS. There are several parameters for general inertial sensors (accelerometer and gyroscope), such as bias, bias drift, scale factor error, non-linearity of scale factor, scale factor asymmetry, dead zone, quantization error, non-orthogonality error, white noise, or random walk errors etc. **Figure 26** illustrates the effect of differences between input and output for some of the major error types.

Avoid "significantly important..." Use "of great importance".

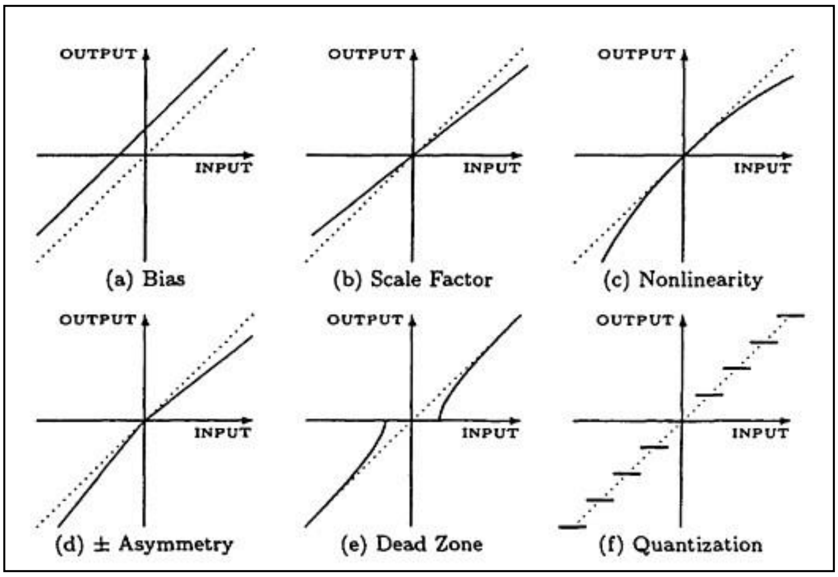

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Figure 26: Common Sensor Error Types (Grewal et al., 2007)

By considering to the major sources of sensor errors, the error models for accelerometer and gyroscope can be defined as:

Equation 29

$$\tilde{\mathbf{f}}^a = (\mathbf{I} - \delta\mathbf{SF}_a)(\mathbf{f}^a - \delta\mathbf{b}_a - \delta\mathbf{nl}_a - \boldsymbol{v}_a)$$

where $\tilde{\mathbf{f}}^a$ is the actual accelerometer measurements; $\delta\mathbf{SF}_a$ is a diagonal matrix of accelerometer scale factor error; $\delta\mathbf{b}_a$ is the accelerometer bias; $\delta\mathbf{nl}_a$ is the accelerometer scale factor non-linearity; $\boldsymbol{v}_a$ is the accelerometer random noise.

Equation 30

$$\tilde{\boldsymbol{\omega}}_{ib}^g = \left(\mathbf{I} - \delta\mathbf{SF}_g\right)\left(\boldsymbol{\omega}_{ib}^g - \delta\mathbf{b}_g - \delta\mathbf{k}_g - \boldsymbol{v}_g\right)$$

where $\tilde{\boldsymbol{\omega}}_{ib}^g$ is the actual gyroscope measurements;

$\delta\mathbf{SF}_g$ is

a diagonal matrix of gyroscope scale factor error; $\delta\mathbf{b}_g$ is the gyroscope bias; $\delta\mathbf{k}_g$ is the gyroscope g-sensitivity; $\boldsymbol{v}_g$ is the gyroscope random noise.

In general, it is assumed that the deterministic part of sensor errors is already compensated through laboratory calibration, such that the full error model for inertial sensors are usually not included for implementation of INS.

-

5.3.5. *Kinematic Equations for Inertial Navigation System*

The ***Inertial Navigation System*** (INS) is the dead reckoning navigation, which is maintained by inertial measurement from IMU for quantifying the changes of position, velocity and attitude of the moving platform. The system navigation is updated through the dynamic models for position, velocity, and attitude updates.

Use "to + verb" to describe purpose, i.e. "IMU to quantify the…"

Equation 31

$$\dot{\mathbf{R}}^n = \mathbf{D}^{-1}\mathbf{v}_e^n$$

where

$\dot{\mathbf{R}}^n = [\dot{\varphi} \quad \dot{\lambda} \quad \dot{h}]^{\mathrm{T}}$ is the changes of geodetic coordinates;

$\mathbf{v}_e^n$ is the velocity vector measured in navigation frame; $\mathbf{D}^{-1}$ is the transformation from velocity vector to geodetic coordinates.

$\mathbf{v}_e^n$

Equation 32

$$\dot{\mathbf{v}}_e^n = \mathbf{f}^n + \mathbf{g}^n - (\mathbf{\Omega}_{en}^n + 2\mathbf{\Omega}_{ie}^n)\mathbf{v}_e^n$$

where

$\mathbf{\Omega}_{in}^n = \mathbf{\Omega}_{en}^n + \mathbf{\Omega}_{ie}^n$ is the sum of transport rate and the Earth's rotation rate;

$\mathbf{\Omega}_{en}^n$ is the transport rate for navigation frame relative to the earth frame; $\mathbf{\Omega}_{ie}^n$ is the Earth's rotation rate in navigation frame; $\mathbf{f}^n = \mathbf{C}_b^n\mathbf{f}^b$ is the specific force in navigation frame, which can be transformed from body

frame;

$\mathbf{g}^n = [\zeta_g \quad -\eta_g \quad g]^T$ is the local gravity vector in the navigation frame.

Equation 33

$$\dot{\mathbf{C}}_b^n = \mathbf{C}_b^n\left(\mathbf{\Omega}_{ib}^b - \mathbf{\Omega}_{in}^b\right)$$

-

where $\dot{\mathbf{C}}_b^n$ is the angular changes of system expressed in navigation

frame;

$\mathbf{C}_b^n$ is the DCM for transformation from body frame to navigation frame;

$(\boldsymbol{\Omega}_{ib}^b - \boldsymbol{\Omega}_{in}^b)$ is the angular measurements corrected with angular changes due to navigation.

Equation 31 is the general differential model for position in navigation frame. The position can be derived through direct integration from the position changes with previous position, which can be implemented by the second-order Runge-Kutta method (Shan and Toth, 2008):

Refer to equations in the text, i.e. "which is represented below in equation 34."

Equation 34

$$\begin{bmatrix}\varphi(t)\\\lambda(t)\\h(t)\end{bmatrix} = \begin{bmatrix}\varphi(t-1)\\\lambda(t-1)\\h(t-1)\end{bmatrix} + 0.5\begin{bmatrix}\frac{1}{R_\varphi + h} & 0 & 0\\ 0 & \frac{1}{(R_\lambda + h)\cos\varphi} & 0\\ 0 & 0 & -1\end{bmatrix}\begin{bmatrix}v_N(t) + v_N(t-1)\\v_E(t) + v_E(t-1)\\v_D(t) + v_D(t-1)\end{bmatrix}\Delta\tau$$

where $\Delta\tau$ is the sampling

time.

From **Equation 34**, the position is updated by integration of velocity. For inertial navigation, acceleration measurements are integrated as shown in **Equation 35** with the differential model for velocity in **Equation 32**.

Equation 35

$$\mathbf{v}_e^n(t) = \int_{t-1}^{t} \dot{\mathbf{v}}_e^n(\tau)d\tau + \mathbf{v}_e^n(t-1) = \mathbf{v}_e^n(t-1) + \dot{\mathbf{v}}_e^n\Delta\tau$$

From the differential models and integration, it can be noted that the navigation updates are strongly dependent on rotation updates. For near-earth application, the magnitude of gravitational acceleration is much larger than usual specific force,

✓ Uses "noted" with subject, e.g. "It can be noted…". It is also possible to use "It should be noted…"

-

such that the propagated position and velocity errors would be critical through the integrates of acceleration errors.

5.3.6. Summary of Inertial Navigation

From the configuration and the process models, it is not difficult to identify the limitations of inertial navigation. By operating the INS in underground railway tunnels, the inertial measurements are corrected with earth rotation rate, transportation rate and gravity acceleration. The estimation of these parameters can already introduce significant errors and being propagated through computation.

Use words and phrase to establish relationships between sentences, i.e. "However, the estimation…"

In contrast with other parameters, the gravity anomaly and error are the most important factors, since the magnitude of gravity acceleration is much larger than usual acceleration for navigation. Consequently, rotation update is more important for decoupling the gravity acceleration from inertial measurements. Such that URLS solution should be considered to be capable of several control factors:

Express non-mathematical results with "as a result" not "such that", i.e. "As a result the URLS…"

1. Continuous velocity updates;
2. Continuous/ semi-continuous position updates;
3. Continuous/ semi-continuous attitude controls.

-

5.3.7. *INS/GNSS Integration*

In addition to the standalone INS, GNSS provides absolute position updates for controlling the accumulation of navigation errors. The integrated navigation was developed for a better solution to achieve relative precision from INS and global accuracy from GNSS.

Start the subsection with a clear sentence stating the purpose of this subsection, i.e. "There are various approaches to integrating INS..."

There are various approaches for integrating INS and GNSS, while Kalman filtering is a common technique for data processing, such as the ***Extended Kalman Filter*** (EKF). The integration of navigation solution is done with compensation with estimated errors, which is implemented by loosely-coupled method or tightly-coupled method.

✓ Uses first sentence of paragraph to sum up main idea of paragraph

Explain technical words as they are introduced.

Also comment on the strengths and weaknesses of the approach.

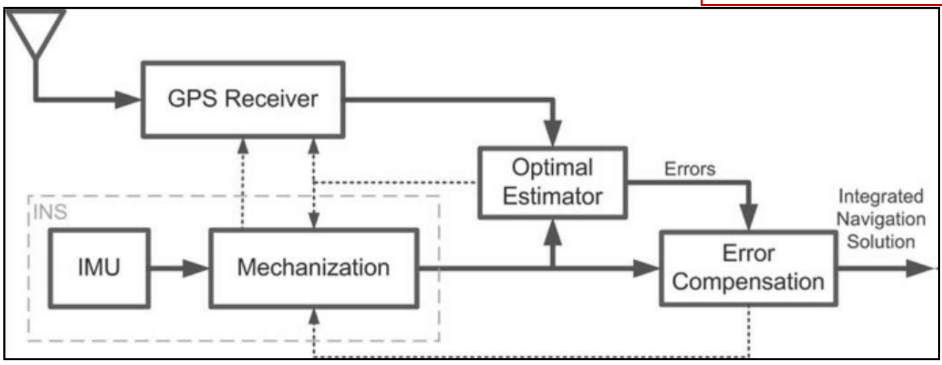

Figure 27: A Typical INS/GPS Integration (Noureldin et al., 2013)

The loosely-coupled method is the simplest form of implementation is done with open loop filtering as shown in **Figure 27** with no internal connection between GNSS and INS. It is derived from the GNSS derived position and velocity measurements for estimating

-

navigation errors with INS derived position, velocity and attitude.

Another integration approach is the tightly-coupled method combining the GNSS-derived pseudoranges with INS estimated pseudoranges as the measurement for the Kalman filter. The close-loop filtering can be used to feedback the estimated navigation errors. The coupling of GNSS can be done with carrier phase observables and instantaneous recovered from cycle slip or reconnection with satellite through the INS estimated navigation.

The purpose of GNSS positioning is to support the inertial navigation for initialization and navigation updates. It is usually implemented by several coupling methods for INS/GNSS integration, which acts as velocity updates and CUPT. Consequently, the GNSS can be decoupled from general INS/GNSS configuration by replacing the velocity updates and CUPT with alternative source of information as mentioned in previous chapter.

5.4. SLAM Implementation

The technique for SLAM implementation including motion estimation, feature extraction and matching, state correction, and filtering is undergoing further studies. It can be a suitable processing technique for enhancing the interaction between measurement and positioning in underground railway.

Clearly state how much research has been done on the topic so far.

Discuss in greater detail how this will be achieved in the current research project.

5.4.1. Localization and Mapping

System motion is controlled by dead reckoning techniques, such as wheel rotations or IMU, which is not necessarily accurate but is capable of approximate localization within certain period of time. The estimated pose (orientation and position) can be applied to transform the mapping data to reference frame.

-

Measurements obtained from laser scanner or photography, mapping data is analyzed by specific algorithms in order to extract features such as points, lines or surfaces. The features are classified for searching and matching with available references so that a transformation from estimated feature positions to the reference feature positions can be determined and applied to the system pose.

> Change tense to discuss future work and work already done, i.e. "pose (orientation and position) will be applied…" or "pose (orientation and position) were applied…"

5.4.2. *Complete Dynamic Solution: SLAM versus MLS*

SLAM solution is usually designed for real-time applications, which can be implemented by different filters. Its computation load is usually minimized by non-rigorous motion model and simplified control processes. SLAM provides a concept of complete dynamic solution combining mapping measurement and navigation estimation.

> Organise comparisons by differences rather than discussing each system in turn, i.e.
>
> Introductory paragraph: stating there are a number of differences in design.
>
> Paragraph 1. Discuss first group of differences
>
> Paragraph 2: Discuss other differences
>
> Paragraph 4: Explain how differences in design lead to the differences in results explained in the next subsections.

MLS techniques focus on acquiring mapping data within a known accurate 3-dimensional navigation solution. It is well-developed for mapping measurement, but its navigation does not rely on mapping data. By comparison, SLAM is a complete and self-contained solution.

The inertial navigation can provide much better estimation of attitude and position for the MLS system platform, while the error control process for IMU is developed with various thorough models, such as instrumental error models, gravity models etc. Under normal operation, the navigation is considered to be accurate for geo-referencing the measurement data in single way.

-

From the original design of MLS, measurement data is seldom used for refining the navigation. Although it is being used for enhancing the performance in GNSS-outage area, the integration of measurement data to system navigation is still limited.

5.4.3. Global and Local Accuracy

The SLAM concentrates in both positioning and mapping, and their integration. The global accuracy of mapping and positioning results can be maintained, while the local accuracy is limited by motion estimation and mapping measurement.

For MLS systems, local accuracy is much higher than SLAM, because the estimation of body motion is well described by inertial navigation process and its error control model. However, accumulated errors for free inertial navigation have to be controlled by alternative control methods. The global accuracy cannot be ensured with standalone MLS.

✓ Uses range of comparative language, e.g. "while", "much higher", "however", "can be better utilized"

5.4.4. Data Processing

MLS system is applied in surveying field to acquire accurate mapping data instead of operating for real-time applications. It is usual to enhance the quality of measurement with post-processing approaches. The applications of using MLS results are usually for planning, surveying record, or analysis, which are seldom directly related to real-time operation.

The use of SLAM can be imitated and applied to MLS technique to broaden the range of its applications. Such that the technique can be better utilized as a multi-purpose solution. The implementation of SLAM for MLS had been studied (Elseberg et al., 2012; Suzuki et al., 2010)., but still has several problems being unsolved.

Link paragraphs using some linking devise, i.e. "In contrast, the use of SLAM..."

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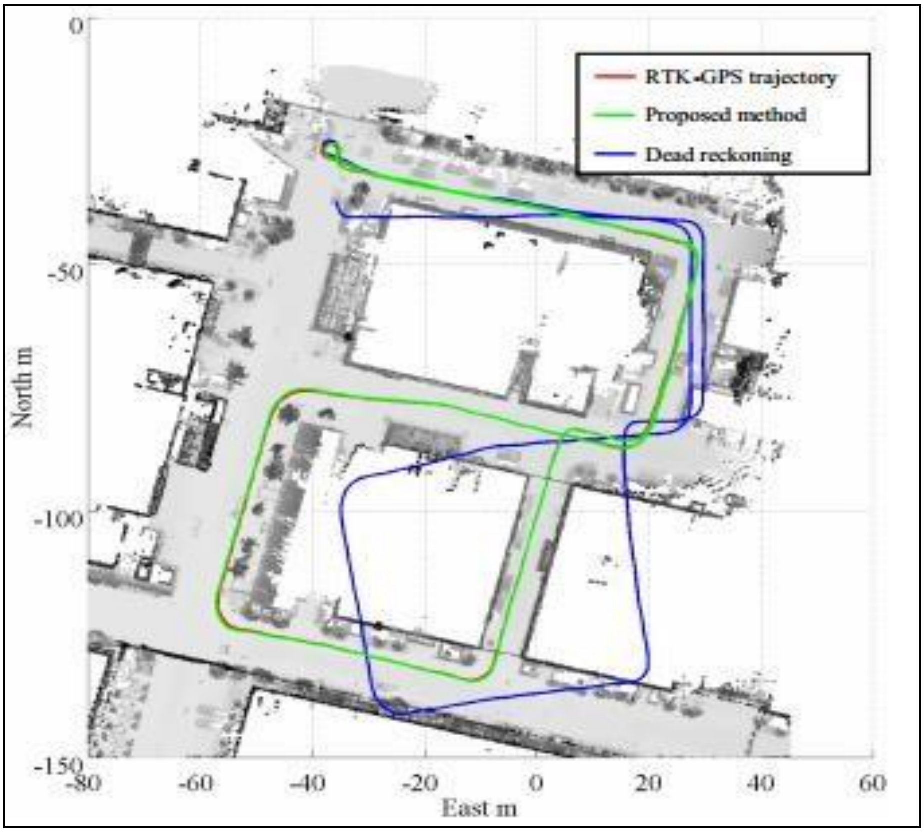

Figure 28: Trajectory of MMS with SLAM (Suzuki et al., 2010)

5.4.5. SLAM in Underground Railway Tunnels

Since the SLAM greatly relies on feature extraction and correcting the self-motion from measurements, the uniqueness of environment is a critical factor. It can perform better if the surrounding mapping environment changes at different locations, such that land marks or features are better identified and matched for closed-loop measurements.

> Use key words with the correct grammatical structure, i.e. "the environment is…", "mapping environmental changes…"

In underground railway tunnels, the rail track and overhead cable are important continuous features. Measurements to these features are matched with their reference positions by projecting the measurements onto the features estimated from alignment data. A correction for

-

transformation can be estimated through ***Iterative Closest Point*** (ICP) with at least three reference features.

However, the underground railway tunnels are elongated structure with smooth tunnel wall. ICP for non-feature matching is not suitable for SLAM correction as the single way navigation in railway system introduces a lack of closure. The performance of SLAM in underground railway tunnels should undergo further studies.

Include a clear summary paragraph or subsection at the end of the chapter.

State more directly the work complete to date, make a clear connection between work discussed in chapter 4 with work done or with work that will be done.

6. Future Work

In the coming future, the list of solutions is to be finalized for verification of correctness. Further studies would be conducted for the integration of various solutions with higher priority.

✓ Introduces chapter with clear statement.

Avoid "in the coming" before the word "future".

Avoid "would" with planned futures.

6.1. Algorithm for Integrating Methods

There is no single and complete method for solving the problems raised in the development of URLS. Instead, various methods can support the Mobile Laser Scanning operation and process in different ways.

-

The definition of methods will be independently formulated with more rigorous mathematical model. The verification will be conducted by simplified simulation tests and under assumptions.

Other possible measurements will be studied, which might be exploited for integration. It is likely that the SLAM approach might be adopted as the integrated solution for processing.

Include a clear timeline of when work is expected to be completed.

The implementation of independent methods will serve as sub-functions of the final approach. The sub-functions of the final solution should be more interactive to enable the flexibility of various situations in railway dynamics.

✓ Uses "will" to discuss work to be done"

6.2. Experiment for Inertial Navigation Measurement

Experimental study will be planned to understand the actual performance of inertial navigation measurement and the quality of rail track geometry.

Do not use "will be planned", use "are planned".

The experiment can be implemented by installing an INS/GNSS navigation system to a rail-guided vehicle and operated in a railway section where GNSS positioning is available.

There are several objectives for the experiment:

1. To analyze the interaction between rail-guided vehicle and the rail track;
2. To examine the performance of INS with and without GNSS;
3. To examine the nominal quality of rail track with respect to alignment data.

✓ States aims in list to aid reader
✓ Uses same grammatical structure with each point on list

The railway section to be selected should consist of various features, such as covering different curvature sections and involving sections with point and crossing. The length of railway section should be long enough to introduce significant INS drift errors for analysis.

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The collected data can be employed to check the performance of several methods.

6.3. MLS Study for Practical Implementation

An attachment programme for exchange study to the University of Calgary will be applied, which aims at studying the implementation of MLS system. It is scheduled with a period of six months, which will start at mid-August, 2014 to mid-February, 2015. Two graduate courses will be taken, which are relevant to MLS navigation: Advanced Physical Geodesy; and Advanced Estimation for Navigation.

> Use first person pronoun when discussing content that directly affects the writer, i.e. I will apply for…"

> ✓ States timeframe and contents

If the application succeeds, it is hoped that practical experience can be gained and sample data from MLS can be obtained for further study, including further development of solution, verification and validation of processing models.

6.4. Verification of URLS Solution

After the stage of individual studies on railway environment and MLS implementation, the proposed solution can be further modified. Verification of the scanning solution would be done by simulating the railway tunnel environment. It is hoped that the final solution can provide an alternative approach for operating the MLS in GNSS-free environment and developing technique towards a continuous URLS solution.

> State clearly when the project will be completed.
> ✓ Finished with restatement of overall project goals, but more detail would be helpful

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Also include appendices with any relevant materials, i.e. publications.

7. References

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