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**How to cite this thesis**

VERIFYING A TERRAIN MAPPING PLATFORM FOR MILITARY VEHICLE MOBILITY

Dissertation submitted for the qualification

Of

Masters of Technology (M-Tech)

In

Electrical Engineering

University of Johannesburg

By

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Supervisor: Prof. B Twala

Co-Supervisor: Mr. David Reinecke

Nov-2016
Declaration

The work I am submitting is my original work and all sources used in the present study have been acknowledged using full references. Furthermore, the present work has not been submitted either in part or in full for any other degree elsewhere or at the University of Johannesburg. Moreover, this work has not been previously published. [1]

Signature___________________ Date _____________________
Acknowledgement

I would like to take this opportunity to thank my supervisor Prof. B Twala and Co-Supervisor Mr. David Reinecke as well as Mr. Martin Mwila for their guidance and support, even in challenging times throughout my research project. Their patience and encouragement were influential in the course of this research. I would also like to thank the Council for Scientific and Industrial Research (CSIR), the University of Johannesburg for giving me the opportunity to further my studies.

I would also like to recognize the productive discussions with my work colleagues. Finally, I would like to thank my family and friends for their encouragement and support throughout my studies. Mom, Nobantu Mzayidume I am forever thankfully for always being there for me. Last I would like to say thank you God for being intentional in seen me through all the challenges and making way for me to further my studies.
Abstract

Vehicles are critical to the military in carrying out functional capacities such as firepower, command and control, protection, sustainment, situational awareness, and intelligence. There is particular need to understand the parameters that will influence the efficient movement of a military vehicle and this can be achieved through researching tire modelling, terrain analysis, and ride comfort. Various research projects have been carried out to understand various subsystems and factors that make up a military vehicle, and they focused mainly on understanding parameters that influencing tire modelling, tire characteristics sensitivity study, terrain analysis and ride comfort. Theoretically, to understand these parameters various studies for on-road conditions have been conducted while less research on off-road conditions has been carried out. In the current century vehicle, technology designs have seen advancement through vehicle simulation, which is less time consuming and reduces the cost of development. Accurate terrain profiles are an integral part of the effective simulation as they are required input. Understanding the ability to measure valid terrain profile accurately is of fundamental importance.

The first contribution of this study is introducing a validation method for off-road profilometer. The second contribution of the study is the validation of the LMT off-road profilometer.

Current validation methods focused on evaluating the accuracy of on road pavement profilers. The method of calibration by excitation and validation against knows obstacles are efficient and thus in the current study this method is incorporated to introduce a validation method which does not depend on known obstacle or terrains. For off-road profiling, the challenge is that off-road terrain is random and changes after every test thus validation through comparison of known obstacle or terrain is thus not possible. The presented method in this study is the laser sensor profile acquisition method developed to validate LMT profilometer off-road, which allows for independent terrain validation and ability to quantify the error found in each measurement. Experimental and simulations are conducted on the LMT profilometer, and the validation of the device is presented, and the RMS error is used to quantify the accuracy of the instrument.
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1. Introduction

Vehicle movement or mobility is affected by elements such as suspension powertrain, load, tires, terrain and environmental conditions. Mobility is the ability of a vehicle to move from point A to B with the assistance of its mechanical power [1]. Vehicles are critical to the military in carrying out functional capacities such as firepower, command and control, protection, sustainment, situational awareness, and intelligence. There is particular need to understand the parameters that will influence the efficient movement of a military vehicle and this can be achieved through researching tire modelling, terrain analysis, and ride comfort.

Various research projects have been carried out to understand various subsystems and factors that make up a military vehicle, and they focused mainly on understanding parameters that influencing tire modelling [2], tire characteristics sensitivity study [3], terrain analysis and ride comfort [4], [5]. Theoretically, these elements are well understood for on-road conditions [6]-[8] while less research on off-road conditions has been carried out. It is crucial to comprehend the interaction between the tire and the terrain for off-road conditions to help gain knowledge for our study of verifying the measurement capabilities of an off-road profilometer used to generate terrain maps.

The terrain input is taken into consideration during the design, to optimize the mobility of the vehicle. The study of the tire-terrain interaction is critical [9]-[11] to enhance the mobility of a vehicle, during vehicle simulation. The simulation model requires the generation of useful terrain profiles as an input to achieve desired results. Computer vehicle modelling simulation has been a preferred method for vehicle analysis because it is a cost-effective method of conducting a theoretical analysis of vehicle dynamics [12]-[15] than conducting the practical test.

A suite of computer simulation software was developed for the South African National Defence Force (SANDF) to enable vehicle technology to be theoretically evaluated, vehicle design to be compared and to develop performance curves and data tables. The suite consists of Mobility Simulation (MOBSim) which comprises of five programs including South African Army Mobility Model (SAAMM). SAAMM focuses on Terramechanics simulation and modelling. Accurate terrain profiles are an integral part of the effective simulation.
1.1 Profilometer Background

Terrain profiling is an application in Terramechanics which mostly focuses on the study of road roughness conducted by measuring surfaces, achieved through the use of a profilometer. Putting terrain profiles into a category such deterministic or non-deterministic allows the ease of distinguishing between them. Concrete pavement road surfaces are deterministic and random rough surface is non-deterministic. In mathematics and physics, a non-deterministic system is a system in which no randomness is involved in the development of future states of the system[16], while a deterministic model is one that produces the same output from a given starting condition or initial state[15]. A longitudinal profile is shown in Figure 1.1, which is an example of a non-deterministic profile that further details elements that make up a profile.

![Figure 1.1: Longitudinal profile: 1-Vertical displacement, 2-Profile, 3-Wavelength, 4-Longitudinal distance][17]

A profilometer had previously been designed and commissioned by Land Mobility Technologies (LMT) to provide terrain data required, as an input into SAAMM, for off-road performance analysis. Multiple tests were conducted using the LMT profilometer as part of the South African Combat Training Centre (SACTC) terrain measurement projects [18]-[21] The last documented operation test of the LMT profilometer was in the 2005 SACTC terrain report[21]. April 2010 Senate presented an evaluation report of the profilometer. The report objective was to evaluate and upgrade the profiling system [22]. The report identified shortcomings of the profilometer and concluded that the device could not make accurate measurements. The report furthermore suggested a new profilometer design be developed which resulted in the need for this study to validate the current system before initiating further redesign.

Profile acquisition methods are used to measure and generate representations of the roads true profile graphically. Computer software is required to process the values to extract the desired information (such as a summary index), while the analysis applied to a profile should is selected based on particular application. The road profile application could be broad such as focusing on road data features that excite primary vehicle system vibration modes, and those vehicle vibrations that degrade ride quality, as well as affecting the vehicle suspension and vertical tire loads, are of primary interest [23].
The current study intends to verify the measurement capability and accuracy of the profilometer and generate verified terrain profile data required for wheeled mobility operation and research. Also, the terrain roughness measurements from the profile can be used to enhance geographic information system (GIS) roadmaps and updating of SAAMM terrain maps.

The required terrain data for use in ride and handling simulation models and these models require point excitation models which are achieved using two-dimensional (2D) data. Three-dimensional (3D) terrain profile surfaces are computationally impractical for these applications and thus currently, profilers 2D data is obtained using single-point lasers that capture localized disturbances [7]. The 2D profile road surfaces are measured along any selected continuous imaginary line path on the surface. Mostly, the profile is measured along two lines, one to represent each wheel track. The type of instrument at time confine the width of measurement or allows the width to be determined by the distance between the wheel of the vehicle axle.

1.2 Contribution of the Dissertation

Successful completion of this project will have a direct impact on off-road military vehicle performance validation research. This study contributes by introducing a validation method for surface contact off-road profilometer. Current validation methods [7],[24],[25] focused on evaluating the accuracy of non-surface contact profilometers. A more detailed study was conducted by Sang-Ho Lee and Sang-Hwa Goo in 2007 [26], but it only focused on developing a standardized measurement system for unpaved roads, and little emphasis was put on the accuracy of the device.

Furthermore, this study will help local road agencies such as South African National Road Agency Limited (SANRAL) with the maintenance of off-road terrain. SANRAL is tasked with the maintenance of South Africa’s (SA) road network and to manage these assets which have an estimated replacement value of R219-billion[27]. It is crucial for SA road agencies and the Department of Transport to ensure that road users are less vulnerable to the effect of improperly maintained roads, which is noticeable to the user by the appearance of potholes and unpaved roads in both rural and urban area [28],[29]. These vulnerabilities are monitored using profilometer data which is used to compute roughness indices a summary of the current state of road networks. Current, road roughness maintenance focuses on paved roads, and not much attention has been given to off-road or rural road balance. This study will bridge the gap by offering a solution and approach to monitoring of off-road networks before and during maintenance.

Although there is much literature on road profiling, it is beyond the scope of this study to talk about all of the literature. However, this study will focus only on profiling off-road terrain or unpaved roads. Profiling of tarred roads, paved roads, and terrain vegetation is lying outside the boundaries of this study. Moreover, profile measurement will be focused on roughness and not obstacles beyond the
wheelbase of the device see Figure 1.2 for more details. The study outcomes will be achieved by answering the following questions. Firstly what are the challenges of off-road profiling methods? Secondly, what is the measurement accuracy of the current LMT profilometer? Lastly, what are the requirements for an off-road profilometer?

Figure 1.2: Types of terrain cover and major problems due to terrain roughness [30]

1.3 Organization of Dissertation

The rest of the dissertation is organized as follows. Chapter 2 describes Literature review and discusses the current systems and methods that are employed and research conducted by industry today in the field of terrain profiling organized based on the relevance to the present study. Moreover, a summary of profile acquisition methods and roughness indices that are used to interpret profile information are presented. Furthermore, it concludes with a critical review process to outline the gap the current study and requirements for an offroad profiler as discussed in the literature. Chapter 3 describes the research instrumentation and the method developed for profile acquisition. Furthermore, this chapter presents the profile arithmetic method developed for validation of off road profilometer. Chapter 4 describes simulation motion study simulation conducted using SolidWorks and test results from the experimental test conducted. Chapter 5 presents the remarks and conclusion of the outcomes from the validation study.
2 Literature Review

2.1 Profilometer Design Literature

Terrain profiling is an application in Terramechanics which focuses on the study of the road surface by measuring terrain using a profiler, while a profiler is an instrument that creates a profile which is an outline of a ground surface, presented as a model, formed in the vertical plane and measured parallel to the ground surface.

A profile is a two-dimensional slice of the road surface taken along an imaginary line. It is always recommended to use paint or visible marking to scribe out a less imaginary line making it easy to obtain repeatable profile measurements, and the approach is to ensure that the line at a constant distance from the centerline of some reference that follows the geometry of the road. Road profiles are frequently measured along two lines per lane, each to represent a vehicle wheel path, but there is no limit to the number of lines for increased profile detail.

It is emphasized that the requirement and validity of the measured profile depend on the intended use of the data. There are multiple industrial applications for a profiler viz. transportation, construction, vehicle design and research. In the construction industry, profilers are used to survey land and to generate geographical maps, while in the transportation and research industry, they are used in road profiling for maintaining and creating maps with characteristics of different terrains and road networks using roughness, road texture and road profile as a comparison [31].

The profilometer design literature of current devices available in the industry is arranged based on the relevance to the current research study. Initial the literature start with the history of the serving tool and then detailing the first well recognized the road profiler designed by General Motors Corporation’s (GM). Secondly, the road profiler currently used in South Africa followed is presented by similar profilometers designs closely related to the current profilometer mode of operation. Followed by the DO-kyung profilometer overview of the functioning of the laser plotting system and method applied to off road profiling. Literature of Can-Can machine presents an off road profilometer that makes direct contact with the ground through implementing a direct surface contact profiling method. Lastly, the Surface roughness profilometer, which operates with direct comparison to the current LMT profilometer with shared similarities, are presented.
2.1.1 Rod and Level

Levelling is a branch of civil engineering that is concerned with the measurement of different points with respect to a fixed point such as elevation of a building or a point taken on the ground[32]. Levelling instruments are distinguished based on the type of method used either direct levelling, trigonometric levelling, barometric levelling, or stadia levelling. Figure 2.1 depicts a levelling tool. Direct levelling is the most used method where direct observation of measurement is read off the levelling instrument. Trigonometric levelling, also called indirect levelling, is a process in which the elevation of the point or the difference between two points is measured from the observed horizontal distance and vertical angle[33]. Road agencies over the world have accepted the rod and level instrument for validating and calibration of industrial profilometers.

![Figure 2.1: Rod and level][31]

From historical origins of levelling is found in the engineering of irrigation canals and aqueducts, it can be seen that all the current levelling principles are based on trigonometric function and the straightforward interpretation of measurement as seen in Figure 2.1. These core principles are easily understood such as trigonometric levelling determined by understanding the mathematical principle of trigonometric triangles. Hydrostatic levelling founded on the method of filling rubber tube or hose with liquid placed at different points of the surface to determine the difference in level or measure similarity. Barometric levelling founded on the principle of atmospheric pressure measured using a barometer that determines height above sea level. Over the years levelling severing tools have been technologically advanced like Astronomical-geometric levelling determined by measuring geodetic latitudes and longitudes where the core method have originated from the depicted theory of the road an level shown in Figure 2.1 all the way to the current study of the mechanical Levelling motorized vehicles to measure terrain surface.
2.1.2 GM Profilometer

In 1964, Spangler and Kelly developed the GM ground surface profilometer based on the dynamic response of a mass excited by the road roughness as seen in Figure 2.2. The profilometer measures vertical displacement in the z-axis of two known mass quantities as they are excited by the road irregularities. The road profile is traced when motion $z_2$ of mass $M$ is measured and added to the measured difference $(z_1 - z_2)$ between the motion $z_1$ mass two of the wheel which follows the ground profile, and motion $z_2$ of Mass M [34].

![Figure 2.2: GMR profilometer [34]](image)

The difference $(z_1 - z_2)$ is determined with a potentiometer and distance $z_2$ with an accelerometer which records acceleration $z_2$; a double integration of $z_2$ gives $\ddot{z}_2$ which, when added to $(z_1 - z_2)$, yields the sought value $z$. An analog computer performs the computation. The profilometer makes use of advanced accelerometer computation algorithms at a hardware abstraction layer which simplifiers the duet of the analog computer as the implementer algorithm is focused at a mechanical analysis which directly interprets the measured profile.

2.1.3 SANRAL Road Survey Vehicle

SANRAL is responsible for planning, designing, constructing, operating, rehabilitating and maintaining South Africa’s national roads[27]. The road agency developed a Pavement Management System (PMS), which is a digital subsystem of SANRAL’s overall assets management system developed for decision-making. The PMS consists of a centralised database, hardware equipment such as the road survey vehicle, and GIS system. In 2006 a road survey vehicle was developed to populate the PMS database with data for conducting road network life cycle analysis. The survey vehicle is capable of collecting data at highway speeds between 20 to 120km/h and capable of collecting on average 500 lane kilometres of data per day. The device uses advanced electronic technologies to acquire data such as distance measuring instruments, accelerometers, gyro different geo position system, and the digital video system. Figure 2.3 illustrates the vehicle.
To provide position coordinates and orientation information a Trimble differential GPS along with an Applanix Initial Navigation system (INS), which acts as a redundant sensor until the GPS fails due to interruptions, are fitted on to the survey vehicle. For height and elevation of the road profile a profilograph equipped with 17 lasers, accelerometers, and gyro sensor is installed in the front bumper of the survey vehicle[27],[36]. The profilograph is used to capture data which will be interpreted to provide road characteristics such as roughness, rutting and texture depth of the road. There are three laser sensors which are 64kHz mounted in the vehicle wheel path positions and one in the centre for texture depth. The other 14 lasers are rated at 16kHz, and when all the lasers are combined, they provide single road lane characteristics. Accelerometers and gyros are fitted on the profilograph to calculate the motion of the vehicle during measurement to compensate for the height of the lasers and account for this motion.

In the current study, the SANRAL profilograph provides a direct point of comparison as has was once tested at Gerotek test range suspension tracks[36]. The suspension tracks were used to verify the LMT profilometer in 2005 [20], and it is a similar area where the Can-Can machine was tested in 2008 [37]. The further makes use of advanced accelerometers, and gyro sensor for compensating for height motion of the lasers, which accounts for errors and overcome aliasing during measurement that is an error inherent in some profilometers.
2.1.4 Do-Kyung Kang, Sang-Ho Lee and Sang-Hwa Goo Profilometer

The Profilometer was designed and developed in Korea for the Agency of Defence in September 2007 by Sang-Ho Lee and Sang-Hwa Goo [26]. The profiler was part of the development of standardisation and management system for the Severity of Unpaved Test Courses Research Project[26].

![Image of Profilometer](image)

**Figure 2.4: Do-Kyung Kang, Sang-Ho Lee and Sang-Hwa Goo profilometer [26]**

The profilometer, as seen in Figure 2.4, is designed in the form of a trailer composed of 4 wheels of equal diameter. The trailer frame motion is described in two degrees of freedom yaw of the front and pitch of rear axle. The trailer is fitted with an air compressor to increase the mass of the trail and reduce trail pitching (see Table 4) for the design specification.

<table>
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<tr>
<th>SPECIFICATIONS</th>
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<td>Overall length</td>
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<tr>
<td>Wheelbase</td>
<td>1.2m</td>
</tr>
<tr>
<td>Compressor pressure</td>
<td>6.86 bar</td>
</tr>
<tr>
<td>Measurement speed</td>
<td>5km/h</td>
</tr>
<tr>
<td>Power requirements</td>
<td>24 VDC</td>
</tr>
<tr>
<td>Sensor type</td>
<td>laser displacement sensor</td>
</tr>
</tbody>
</table>

**Table 1: Do-Kyung Kang, Sang-Ho Lee, and Sang-Hwa Goo profilometer specification**

The theory of operation of the profilometer is based on an algorithm which makes use of the pitch angle $\theta$, roll angle $\%$, and vertical distance measurement[26]. The vertical displacements are measured both on the left and right sides of the trailer and are described by LAS_l and LAS_r respectively, including the sampling interval (dl). The image below describes the path of the laser displacement sensor (see Figure 2.5).
The final profile data is normalized to represent the observed profile, and this is best explained by the linear interpolation equation presented below. Where $y_{lm}$ and $y_{rm}$ are the final left and right profile respectively, while $y_{r}$ and $y_{l}$ are the right and left terrain profile data. The error due to approximations is reduced by decreasing the sampling interval ($dl$) and $x_{r}(i)$ is the normalised i-th sampling interval.

\[
\begin{align*}
y_{lm} &= y_{lR}(i) + (x_{r}(i) - x(i)) \tan(\theta(i)) \quad (2.1) \\
y_{rm} &= y_{rR}(i) + (x_{r}(i) - x(i)) \tan(\theta(i)) \quad (2.2)
\end{align*}
\]

### 2.1.5 Can-Can machine

In 2008, Carl Martin Becker developed the Can-Can Machine, as shown in Figure 2.6, as part of his Master’s thesis at the University of Pretoria[37], and this machine is a mechanical measurement device designed in a right angle triangular shape and fitted with wheels on each corner [37]. The principle of operation of this device is based on the observation of human fingers, which, when moved over a rough surface, follow the structure of that surface.

![Figure 2.6: Can-Can machine](image-url)
The device consists of thirty arms mounted on the rear of the structure, which is at 100mm apart. These arms allow the user to measure a 3m wide section of terrain. The device profiles the terrain by calculating the displacement at the tip of each arm, and this is achieved by measuring angles at the pivot point. Analogue readings are captured through a 2W, 10kΩ single turn potentiometer, mounted on each arm. A 5V, 12bit Analogue-to-Digital Converter (ADC) is used to convert the analogue reading to digital data. The combination of the potentiometer and the ADC has a resolution of 0.98mm [37].

The profilometer speed adjustment is set at 0 to 1km/h to achieve a slow walking pace. The driving wheel is fitted with an encoder to measure the displacement on the x-axis. The encoder is also responsible for digitally triggering the acquisition system. The frame is fitted with a CXTA02 tilt sensor to take into account of the rolling and pitching experienced due to the irregular terrain. Due to the irregular terrain, the device needs to measure a fixed reference, and the tilt sensor obtains the reference angle.

The theory of operation of the Can-Can machine is better described by the measurement arm, as shown in Figure 2.7, which has a specified length (L) and an initial reference measurement height of 197mm offset above the surface. The measurement height describes the maximum obstacle that the device can measure. The tip of the arm is mounted to a potentiometer at the origin point (0, 0) which measures the angle of the arm. The potentiometer gives a voltage reading output which varies due to change in surface and can be interpreted as the equivalent of the maximum angle being β which is a summation of the initial angle θ₀ and measured angle θ. This can be seen mathematically in the equation below[37].

Reference

\[ Y = -L \sin \beta + 197(\text{ground reference}) \]  \hspace{1cm} (2.3)

![Figure 2.7: Can-Can machine measurement arm [37]](image-url)
2.1.6 Surface Roughness Meter

Figure 2.8 depicts the Surface Roughness Meter built by the University of Michigan Institute of Science and Technology for the U.S Army's land locomotion laboratory [34]. The ground profile measuring assembly is attached to the rear unit of the towing vehicle using a pivoted support which allows the trailing arm to rotate in yaw and pitch.

![Surface Roughness Meter](image)

Figure 2.8: Surface Roughness Meter[34]

Two wheels of equal diameter are mounted adjacent to one another to measure the terrain slope. The measuring wheels are fitted with an odometer which gives a voltage reading to record the distance travelled. There is a synchro system which is mounted on the trailing arm which is connected to the measuring wheels. The attached synchro systems indicate the angle between the wheel frame and the trailing arm. There is a second synchro attached to the pivot support on the trailing arm which measures the angle between the trailing arm and the vertical spin axis of the gyroscope[34].

2.1.7 LMT profilometer

The profilometer developed by LMT for terrain profiling was designed in a T section outer dimension measuring 5m long and 1.9m in width (see Figure 2.9). Instrumentation used in the profilometer consists of the following sensors: four displacement transducers to measure the vertical displacement; encoder mounted on the motorcycle wheel used as a trigger for data acquisition, speed. Longitudinal distance measurement; are conducted using dual axis tilt meter mounted on the main frame (front), while to measure the roll and pitch angles of the frame; two single axis tilt meters mounted on the measuring arms to measure the arm angle; Global Positioning System (GPS) with antenna and receiver unit is used to relate the road roughness to the travel distance[20].
There are two measuring arms set distance apart from each other, responsible for profile measurement of two wheel paths, and the distance between these two arms is measured to compensate for body roll of the frame when processing data. The profiler is capable of measuring long wavelengths of up to 10m which influence ride comfort, and the measuring arms can be adjusted to measure any width track with a maximum limit of 1.8m [20].

In 2005, the test report and manual for the profilometer was published [20]. Further evaluation of the device was carried out in April 2010 and presented in a report by Senatle titled Repair, Upgrade and Re-commission Profilometer [22], and all the data for this report was taken from the 2005 profilometer manual [20]. Supporting conclusions from the Christo Koen were based on a bicycle model explaining the profilometer which identified shortcomings of the profilometer and concluded that the device could not make accurate measurements[38]. The findings resulted in the need for the current study to verifier the measurement capabilities of the profilometer by conducting the experimental test.

The dynamic analysis reported by Senatle was firstly based on the observations that pitching of the profilometer frame would produce inaccurate readings because the terrain changes vertically as measured by the small wheels are relative to the moving frame as shown in Figure 2.10. Additionally, Figure 2.10 depicts tangential velocity (or), frame angle (θp), measurement arm angle (θa) and change in elevation (yt) which have two major points of motion labelled as A and B.
Secondly, the analysis places further emphasis on how the error will occur when measuring profiles with wavelengths equal to that of the profilometer length (i.e. $l = n\lambda$) as depicted in Figure 2.11. In the figure the length of the frame is ($i$), the road wavelength is represented by ($\lambda$), while the ($n$) is any an integer ($n=1, 2, 3$).

Furthermore, the study stated the variance in measurements where the small sine waves at Gerotek are 100 m long, while profilometer results indicate that they were approximately 120m as shown in Figure 2.12. The figure highlights the inaccuracy of the optical tachometer used for taking the measurements.
Moreover, a mathematical bicycle model was developed by Christo Kone [38] and executed in MATLAB® to simulate the operation of the profilometer. The profilometer model is based on a bicycle model, while the terrain profile was simulated by taking into account the Gerotek profile of a period of 1.8 m and amplitude of 0.6 m, and the terrain is further defined as both amplitude and period of a sinusoid. The conclusion was drawn, and the following observations were made: firstly, that there is a phase shift in the measured profile from the actual profile; and lastly, the real and measured amplitudes are different, and the maximum error is 64.1% due to shifting. The report further concluded that the system is flawed since it measures profile relative to a moving reference and therefore cannot make accurate measurements.

The need for the current study is based on verifying the measurement capabilities of the profilometer by performing an experimental test on the device. This present study differs from Christo Kone study as it initially develops a mathematical model for terrain computation of the profilometer then proceed to analyze the operational capabilities of the current LMT profilometer and thus set it apart from the previous studies conducted on the LMT profilometer in the past. Furthermore, the study differs from current research studies conducted in the industry as it is specified at off-road profilometer and the verification process applied to the LMT profilometer.
2.2 Profile Acquisition Literature

2.2.1 Gridding Method

The grid terrain measurement method was implemented in the high-fidelity vehicle as seen Figure 2.13 used for terrain measurements research [39],[40],[41] at the Virginia Polytechnic Institute and State University.

![Vehicle Terrain Measurement System (VTMS) [39]](image)

Figure 2.13: Vehicle Terrain Measurement System (VTMS) [39]

A 3D laser scanner is fitted on the VTMS that transversely collects data through the application of a rotating prism. Figure 2.14 illustrates how the scanning laser collects data at equal angles of rotation shown as θ, while depicting the different transverse spacing between measurements shown as x1, x2, and x3 taken on the surface. Furthermore, the image details the scanner error where the measurement points are closer to the centre of the scan than at the edge of the scan. This issue is exacerbated when vertical undulations are present, transverse spacing between points is not consistent while introducing motion the longitudinal direction results in the spacing between the point being controlled by the host vehicle speed and scanner frequency [42]. Grading is introduced to generate an effective terrain surface from the measured data for simulation purposes.

![Schematic of consecutive non-uniformly spaced laser samples][39]

Figure 2.14: Schematic of consecutive non-uniformly spaced laser samples [39]
A grid process is a method used to generate a compact terrain surface readily accessible for simulation. Figure 2.15 illustrates the measured surface terrain data which forms a point cloud of terrain height at random locations in the horizontal plane. The red axis longitudinal (u) and vertical (v) in Figure 2.15 represents path-specific coordinate system traversed by the host vehicle. The term “irregularly spaced” implies that raw data analyzed from a measured, mapped area will appear randomly dispersed meaning the distance between points is inconsistent over the map as seen in Figure 2.15 represented by blue dots. The method of gridding is used to produce regularly spaced Z array values from the supplied irregularly spaced XYZ data. The required terrain profile represented by horizontal and vertical locations of regularly spaced grid nodes are defined by interpolation algorithms based on known data observations.

![Figure 2.15: Irregularly spaced data obtained by terrain measurement system [42]](image)

### 2.2.2 Basic Function

Terrain profile generation has seen significant consideration over the years with multiple researchers using different experimental study’s to arrive at an arguably similar conclusion. The first study measured variations in forces F as seen at the wheel hub caused by the passing of a tire over an obstacle while using various inflation pressures and tire deflections. During the study, Bandle and Monguzzi witnessed the process of terrain pre-filtering as the study results introduced the existence of a basic curve [43],[8]. The study was conducted as illustrated in Figure 2.16.

![Figure 2.16: Laboratory test with a dynamometric hub in fixed position [43]](image)
The observation made from the experiment indicated that the existence of a basic curve was independent of the tire deflection. The width of the force variation was seen to be propositional to the vertical stiffness of the tire and independent of the inflation pressure. The basic curve is capable of being transformed by dividing it by the vertical stiffness of the tire and by doing so the basic curve no longer represents a force but a displacement [44]. The curve can then allow for interpretation of the obstacle shape which results in a geometrically fitted road profile. Figure 2.17 further taken from a study conducted by Zegelaar illustrates how asymmetrical obstacle can be obtained by summing two equal but shifted sine waves[8]. The height of the sine wave is denoted by \( \frac{1}{2}H \) the width by \( \lambda_{bf} \) moreover, the shift of the second sine wave by \( \lambda_{imp} \) [8], while a similar basic function is used to represent the effective plane angle.

**Figure 2.17: The composition of the effective road surface from basic functions for an obstacle** [42]

The basic function is widely for effective terrain profile generation. Pacejka introduced the two-point follower technique to compute the effective terrain profile based on core function curves, as shown in Figure 2.18 [45]. The basic curve is defined to be assessed at constant vertical load when rolling over a trapezoid obstacle with a deficient speed. The horizontal projection of the segment defined by the two points is kept to be a constant. The midpoint height of the two points moving along the basic curve is considered to be the description of the equal road height.

The two-point follower technique introduces using a single basic curve with full height \( h_0 \) and two points moved along the curve. The midpoint of the two point segment which is kept at constant length describes the characteristic of the effective road height \( W \). The basic curve parameters are described as follows the ength \( l_b \), the shift is \( l_s \) moreover, the offset is \( l_f \). After multiple experiments, it turns out that this method simplifies road height \( W \) as it is equal to the change in axle height as seen in Figure 2.19. The division of vertical forces by radial stiffness as curve length \( l_b \), and shift \( l_s \) are independent of vertical force. The curve length may be estimated from the circle curve length or calculated by the formula below. The horizontal shift \( l_s \) was found to be approximately 80% of the curve length[45].
Figure 2.18: The effective rode response results from the basic curve [45]

Figure 2.19: The rigid wheel rolling over an obstacle [45]

\[ l_b = \sqrt{r_0^2 - (r_0 - h_{step})^2} \] (2.4)

2.2.3 Slope Integration Method
Irvin J. Sattinger from the University of Michigan developed and tested a profile measurement device as part of a research study on terrain profiling. In the study, various consideration of possible methods of measuring terrain geometry was carried out, and the Slope Integration method was selected to base the theory of operation of the developed device[46],[47]. The device integrates the slope of the ground as described in equations discussed below [46].

\[ y - y_0 = \int_0^S \sin \theta ds \] (2.5)

\[ x = \int_0^S \cos \theta ds \] (2.6)
Where:

- $S$ is the total distance travelled along the ground surface
- $x$ is the horizontal component of distance along the ground for total distance $s$
- $y$ is the elevation of the ground at horizontal distance $x$
- $y_0$ is the elevation of the ground at the beginning of the run
- $\theta$ is the slop angle of the ground under the vehicle at distance $s$ from the origin

![Diagram with labels](image)

Figure 2.20: Slope integration model [47]

In data processing, the increment of horizontal distance travelled $\Delta x$ and elevation $\Delta y$ of the ground are computed for constant increments $\Delta s$ along the ground surface to achieve measurements that best represents the profile see Figure 2.20 for the diagram representation of the slop integration model.

\[
\Delta x_i = \Delta s (\cos \theta)_i \quad (2.7)
\]
\[
\Delta y_i = \Delta s (\sin \theta)_i \quad (2.8)
\]
\[
\therefore \ x_i = \sum_{0}^{i} \Delta x_i \quad (2.9)
\]
\[
\therefore \ y_i = \sum_{0}^{i} \Delta y_i \quad (2.10)
\]

### 2.2.4 Accelerometer Integration

Acceleration is defined as the rate of change of velocity of an object furthermore velocity is the rate of change of position of the same object[48]. Mathematically the position of is obtained through double integration when given the acceleration the object.

\[
v = \int \vec{a} \, dt \quad \text{and} \quad \vec{s} = \int \vec{v} \quad \therefore \int((\vec{a}) dt) \, dt \quad (2.11)
\]
Integration of acceleration tends to produce an error because it approximates the underlying signal. The measured signal might contain noise, and the integration of noise leads to output that has a root mean squared value that increases with integration[49]. Multiple methods exist and algorithms that require the initial condition of position and velocity to be known [50, 51]. An alternative method referred to as the trapezoidal method reduces the errors of numerical integration as seen in Figure 2.21 and furthermore offers more flexibility by not requiring any initial conditions. This gives the first order approximation of the signal through interpolating the first are the value of the previous sample (a square), while the second area triangle formed between the previous sample (sample n-1) and the actual sample (sample n) divided by two[48] and mathematically seen below.

![Figure 2.21: Errors of integration are reduced with a first-order approximation (trapezoidal method) [48]](image)

\[
\text{Area}_n = \text{Sample}_n + \left[ \frac{\text{Sample}_{n-1} - \text{Sample}_{n}}{2} \right]
\]  \(2.12\)

Mathematically the trapezoidal integration can be represented by the following differential equation [49] where \(x\) is the integrand, \(y\) is the output of the integrator, and \(f_s\) is the sampling frequency.

\[
y_n = y_{(n-1)} + \frac{1}{2f_s} \left[ x_{(n-1)} + x_n \right], n > 0
\]  \(2.13\)
2.3 Profile Modelling Literature

2.3.1 Roughness

Roughness is used to describe the relative degree of comfort or discomfort experienced by a road user when using a road and it is a fundamental aspect of monitoring in network surveys since it serves as a composite measure of road condition and its effect on road users. The variations along the wheel paths can be quantified through a measured profile of the road in the direction of the vehicle travel (i.e. the longitudinal profile) [24].

The Guidelines for Network Level Measurement of Road Roughness documented by the South African Committee of Transport Officials states that only certain wavelengths making up a profile are necessary for roughness estimation. A significant influence on road user comfort is only notable with wavelengths between 1 m to 30 m, and such wavelengths are critical for roughness measurement. On the other hand, the measured profile is typically filtered to remove non-critical wavelength components from the profile before calculating roughness parameters, and these non-critical wavelength components consist of all those that are outside the 1 m to 30 m wavelength band. The measured profile contains the information that can be used to assess the perceived road roughness [52]. Moreover, ISO 8608 1995 recommend that, during measurement, a roughness parameter should be determined, by a profiler, over a fixed segment (e.g. a 10 m or 100 m length) of a profile. Currently, response types, high speed, and static profilers are the three widely used road roughness profilers [24].

Response Type devices operate by measuring the change in the suspension of a vehicle or towing a trailer and interpret the profile by using filters to translate the measured change into roughness parameter[53]. The computed parameter is called the Average Rectified Slope (ARS), and its SI unit is expressed by (mm/km), and this is achieved by when the summed mm travelled are divided by the length of the test section. Depending on the required outcome or use, the profile is further filtered and processed mathematically to produce a simulated ARS value, or to produce another roughness index [24].

The advantage of response type device is that they are relatively inexpensive when purchasing, calibrating and maintaining in general perspective purchasing is 1/10Th of the cost of a high-speed device. Furthermore, these devices have been widely accepted by many engineers, and this has been because in general the outputs of the instrument are known to agree with engineers’ assessment of roughness and pavement conditions. Some disadvantages are inherent to response type devices such as the precision of the instrument which performs lower than a Class 1 profiling device. The lack of high precision introduces measurement errors which include deterioration of International Roughness Index (IRI) value of a typical road section caused by errors due to calibration thus affecting the reputability of the device measurements.
Since 1960, GM was leading in the research and design of high-speed profilers. Over the years, these devices have seen a growing interest and have been widely accepted because of their precision and advanced technology. Amongst the early adopters of the instrument is road and transport maintenance agencies, but this high-speed device also known as Inertial Profiler derives its name from the use of accelerometers to determine an inertial reference which provides the instantaneous height of the measurement platform the motion of the vehicle [24]. These devices are capable of measuring terrains at high speed more than 100km/h and increasing profile measurement detail by measuring multiple wheel paths at one given an instance.

The Inertial Profiler first obvious advantage is that is physically mounted on a measurement vehicle, and thus it simplifies logistics. Furthermore, the benefit of this device is that the device employs the use of multiple sensors. A height sensor accelerometer and a distance measuring system with an onboard computer to process and store data outputs instantaneously; it is very versatile allowing the user to configure specific outputs and sensors for use from the laser, optical, inferred and ultrasonic given a high precision output. However, it has disadvantages because it employs lasers which inhibit it from measuring off-road or rural road networks. Moreover, the cost of the device and lack of local test experts propels the local road agencies to book international test experts and thus impacting negatively on the agencies’ budget. Validation of experimental data and the device is a difficult process and poses a disadvantage to road agencies as this process is very costly and time-consuming requiring in-depth knowledge of the operation of the profiler.

Static profilers are used to calibrate and validate both the response type and the high-speed profilers respectively by correlating the IRI outputs of several test section. Static profilers are the highest precision which Class 1 type and many high-speed devices are capable of produce Class 1 measurement precision but don’t offer 100% controllable test outputs, while static device offers increased repeatability during calibration, and its slow speed, during measurement, assists in achieving this.

2.3.2 Roughness Index

Over the years, roughness has been used as an indicator for road condition both locally and internationally. From this observation followed a need for a common roughness measures for correlation and transferability of measured data from various profiling instruments. The International Road Roughness Experiment (IRRE) was held in Brasilia, Brazil in 1982, and it was conducted by research teams from Brazil, England, France, the United States and Belgium to define a standardized roughness scale[54].

The IRRE tested a profilometer that measures the longitudinal elevation profile of the road, and a response type profiler, which integrates readings of the device into an instrument-specific numeric. The experiments demonstrated that a correlation exists between the response type profiler and profilometer
records, and it has verified that they could all be calibrated to a single roughness scale without compromising their accuracy. After evaluating a large array of possible standard indices, the IRI was the index selected from this method.

Since the publication titled the Guidelines for Conducting and Calibrating Road Roughness Measurements, funded by the World Bank Technical in 1986, the IRI became the most widely used reproducible indicator for road roughness[54], [55]. The IRI is obtained by applying a mathematical transform (computer algorithm) to a measured profile in a single wheel path. The algorithm is designed to simulate the movement of the typical passenger car suspension called the quarter car model moving at 80 km/h, to produce a simulated ARS value.

The IRI interpretation scale ranges from zero to 16. Please note that for all road categories, an IRI value above the upper reference limit indicates that the road is too rough to be considered in that category as enshrined in Figure 2.22. For newly paved roads, the measured IRI ranges from a lower limit of 1.5 m/km to an upper limit of 3.5 m/km. For unpaved roads, the measured IRI ranges from a lower limit of circa 5 m/km to upper limit of 15 m/km. The IRI offers a distinct advantage over the response type measurement because the IRI calculation employs an algorithm which naturally remains constant over time as opposed to an actual vehicle to transform the profile into an ARS value.

![Figure 2.22: The IRI interpretation scale](image-url)

[24]
**International roughness index**

The IRI is worldwide accepted roughness index which is based on the simulation of the roughness response of a Golden car model travelling at 80km/h, and mathematically it is a reference average refined slope of an accumulated suspension motion of a vehicle divided by distance travelled during the test[56]. The IRI is calculated in four steps; firstly the aim is to convert the profile to a slope, secondly, apply moving average filter of 250 mm, thirdly simulate the response of the “Golden Car” model and lastly accumulate the average rectified value of the result[23]. The Golden Car model seen in Figure 2.23 calculates the spatial derivative of the stroke in response to the suspension to the profile l with standard settings for speed and the vehicle properties. These values are as follows: \( V = 80 \text{ km/h}, \ mu/\text{ms} = 0.15, \ kt/\text{ms} = 653 \text{ 1/sec2}, \ ks/\text{ms} = 63.3, \ 1/\text{sec2} \) and \( cs/\text{ms} = 6 \text{ 1/sec}. \)

![Quarter car model](image)

**Figure 2.23: Quarter car model[23].**

It is without the uncertainty that no matter what index is calculated from a profile the quality of the information is only as good as it profiler and the guideline for longitudinal pavement profile measurement state this clearly [57]. The IRI standard requires 167mm sample interval and lower to compute accurate measurements, while during sampling a proper anti-aliasing filter is recommended to be applied to the elevation sensors and accelerometer signal before at the initial stage of analysis.

**2.3.3 Measurement classes and devices**

In the paper titled Guidelines for Conducting and Calibrating Road Roughness Measurements, by Sayers et al. (1986) presented a general classification method for roughness measurement devices which distinguish between all types of roughness measuring instruments [56]. The method grouped roughness measurement devices into four generic classes by where their measures lie on the IRI scale, which in turn affects the calibration requirements and the accuracy associated with their use.
The classification was presented because no instrument is perfect, an error exists. Error levels are traded off against the cost of the device and the effort needed to use them. The four main classes of roughness measurement devices, as defined by Sayers et al. (1986) are summarized in Table 1. It will be noted on the table all devices that are capable of measuring an accurate road profile fall into Classes 1 and 2. Response type devices that have been calibrated before measurement falls into Class 3, while subjective ratings and uncalibrated response type devices constitute Class 4 [58].

Table 2: Classes of Roughness Measurement [58]

<table>
<thead>
<tr>
<th>Device Class</th>
<th>Class Requirements or Characteristics</th>
</tr>
</thead>
</table>
| Class 1: Precision Profiles | • Highest standard of accuracy measurement  
• Requires precision measurement of road profiles and computation of the IRI  
• 2 percent accuracy over 320 m  
• IRI repeatability of roughly 0.3 m/km on paved roads  
• IRI repeatability of approximately 0.5 m/km on all road types |
| Class 2: Non-precision Profiles | • Requires measurement of road profiles and computation of the IRI  
• Includes profiling devices not capable of Class 1 accuracy |
| Class 3: IRI Estimates of Correlations | • Does not require measurement of the road profile  
• Includes all response type devices  
• Devices are calibrated by correlating outputs to known IRI values on specific road sections |
| Class 4: Subjective Ratings and Uncalibrated Devices | • Includes subjective ratings of roughness  
• Includes devices for non-calibrated response and profilometric devices |

Further definition is needed to distinguish between classes since profile devices in classes 1, and 2 often share some similarity. These definitions of requirements are specified based on the sampling interval and the precision of the elevation measures as summarised in Table 3.
Moreover, the American Society for Testing and Materials (ASTM) Standard E 1364-95 requires further details to differentiate between the class 1 reference devices and the class 2 inertial profiler. Class 1 devices were observed to produce valid evolution points with the ability to reproduce the actual profile travelled along a wheel path, while Class 2 devices provided sufficient accuracy for IRI without the reproducibility of the class 1 device. The standard requires vertical resolution that depends on roughness and the incorporation of the IRI range as listed in Table 4 [23].

Table 3: Accuracy Requirements for Inertial Profilometer [58]

<table>
<thead>
<tr>
<th>Device Class</th>
<th>Maximum Longitudinal Sampling Interval (mm)</th>
<th>Vertical Resolution (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1</td>
<td>&lt; 25</td>
<td>≤ 0,1</td>
</tr>
<tr>
<td>Class 2</td>
<td>25 &lt; and ≤ 150</td>
<td>0,1 &lt; and ≤ 0,2</td>
</tr>
<tr>
<td>Class 3</td>
<td>150 &lt; and ≤ 300</td>
<td>0,2 &lt; and ≤ 0,5</td>
</tr>
<tr>
<td>Class 4</td>
<td>&gt; 300</td>
<td>&gt; 0,5</td>
</tr>
</tbody>
</table>

Moreover, the American Society for Testing and Materials (ASTM) Standard E 1364-95 requires further details to differentiate between the class 1 reference devices and the class 2 inertial profiler. Class 1 devices were observed to produce valid evolution points with the ability to reproduce the actual profile travelled along a wheel path, while Class 2 devices provided sufficient accuracy for IRI without the reproducibility of the class 1 device. The standard requires vertical resolution that depends on roughness and the incorporation of the IRI range as listed in Table 4 [23].

Table 4: Resolution Requirements[23]

<table>
<thead>
<tr>
<th>IRI Range (m/km)</th>
<th>Resolution(mm)</th>
<th>Class 1</th>
<th>Class 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0-0.05</td>
<td>0.125</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>0.5-1.0</td>
<td>0.25</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>1.0-3.0</td>
<td>0.5</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>3.0-5.0</td>
<td>1.0</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>5.0-7.0</td>
<td>1.5</td>
<td>3.0</td>
<td></td>
</tr>
</tbody>
</table>
2.3.4 Validation

Profiler validation is done to validate a profiler on accuracy, and to determine that individual component of the system is calibrated and function correctly. The second objective of validation is to confirm that the approach adopted and employed by the profiler can provide consistent results in the required format. Because validation is time-consuming and costly, it is important to define the level of and precision requested by the profiler, which depends on the intended use. Profilers have a limited range of application, for instance, the highest level of attention is needed to assess road network deterioration and for which the outputs will drive planning models, while a low precision is acceptable for a profiler used to prioritize road network maintenance and rehabilitation [24].

It is acknowledged that no instrument is perfect and there exist errors for each system and thus trade off against the cost of the instrument, level of precision and efforts required to use the instrument. Profilers are accepted as valid for obtaining statistical values that are comparable to a statistical value that would be calculated from the actual profile while keeping into account that the measures obtained for a selected statistic such as IRI are neither high nor low but are on average when compared. Furthermore, it is noted that determination of the statistics does not give the accuracy of the system, but it verifies that the outputs coming out of the device are reasonable. Consequently, if a statistical value from a given profiler is systematically biased relative to an accepted reference, and the results are 20% high for some test then the profiler is not valid for that statistics and should not be used to obtain that statistics[55].

When checking the operation of a profile, the first step is to ensure that produced outputs are reasonable. Secondly, conduct calibration on individual instruments that make up the system, while verifying every single sensor’s free function as defined by the manufacturer. Consequently, colouration of measured values is required, which is the process of analyzing the mutual relation or degree of correspondence between variables. Calibration by correlation is not a recommended practice for inertial profilers, while it is the only way to calibrate response-type devices, and this all depends on the dynamic response properties of the measurement vehicle. The setting of limits for which a profiler is valid is very crucial in achieving the required outcomes for a specific application [31], [55].

What Causes Profiling Error?

A profiler follows a line on the road during measurements, and each time it measures a road it creates different lines that aim to emulate the surface profile. The line location being profiled is defined by two variables: the longitudinal start position and the lateral position. These variables precisely define the starting point; however, a profiler is made up of multiple parts which have inherent errors, and collectively all these subsystems form part of the profiler’s measurement errors. For instance, displacement transducers, require constant calibration due to offset drift over time, and in the instance of the laser scanners, contact surface type and light induce errors, so continual monitoring of the application is required [31].
Errors associated with profiling includes temperature changes which vary the calibration of resistances-driven displacement transducer because a change in temperature affects resistance; sampling error represented in the form of aliasing, a misidentification of a signal frequency resulting in distortion or error. Furthermore, there is a human error in the use of the profilometer in attempting to define its validity by using repeatability as a measure of accuracy.

Repeatability is the ability to obtain repeatable measurements over time with the same instrument [59] it is mostly used in diagnostics application to define the variation of profile indices taken in each test. When measuring repeatability on the surface profile it is usually recommended profiles be made in a short space of time, but it does not affect mean value obtained for a profile which is the outcome of calculating roughness index[60]. However, portability is, the ability to replicate measures with a different profile, from a different manufacturer, of the same design, while portability is defined as the capacity of the profiler to replicate measurements of an entirely different profiler design [31],[60].

**Mean Absolute Error**

Absolute error is the amount of inaccuracy in a sampled or modelled measurement seen as the difference between the measured value and true value. The Absolute error is also known as the Absolute Accuracy error and seen as the difference between experimental value and the actual value[61]. The formulae of absolute error given in the form ∆y is:

\[ \Delta x = y_i - y \]  \hspace{1cm} (2.14)

Where \( y_i \) is the measurement and \( y \) is the true value. The Absolute error is expressed in the form of coordinates in the input coordinate system which means if the data file coordinates are profile input the RMS error is conveyed in the form of distance. The Mean Absolute Error (MAE) is the average of all the absolute error and is used in statistics to forecast how close predictions are to the model outcomes mathematical given as[61],[62]:

\[ MAE = \frac{1}{n} \sum_{i=1}^{n} |y_i - y| \]  \hspace{1cm} (2.15)
**Root Mean Square Error**

Root mean square error (RMS) is a measure of magnitude used to determine the difference between predicted and observed values. The RMS error determined by taking the standard deviation of the residuals over the number of samples all squared. Residuals are the difference between value and predicted values grasped as the Absolute error. In the coordinate system, the x residual is the difference in the input and transformed coordinates in one direction, while y residual is the difference in the input and transformed coordinates in another alteration[63],[64]. Mathematically the RMS error is explained as follows.

\[
RMS\ error = \sqrt{\frac{\sum_{i=1}^{n}(\hat{y}_i - y_i)^2}{n}} \quad (2.16)
\]

Where \(\hat{y}_i\) is observed value and \(y_i\) is the measured or predicted value.
2.4 Critical Review

Nearly all road roughness devices function as mechanical filters to remove the long wavelengths and focus on wavelengths that affect vehicle ride and vehicle system vibration modes. Road slopes and unwanted long wavelengths undulations sometimes dominate unfiltered road profiles. Low-speed rolling devices filter the profile through their geometry, while the moving average based length normalizes the wave numbers. One of the challenges when mapping irregular terrain is validating the device and accounting for the introduced filtering and errors due to the motion of the instrument.

Sang-Ho Lee conducted the study [26] indicated that some inaccuracies could be experienced after normalizing the data by the use of interpolations methods, and such errors are due to pitching and rolling motion of the trailer during measurement. Inherent instrumentation errors such as for the laser displacement sensor that occurs need to be quantified, and this achieved by corresponding sampled data to equal increments of motion travelled in the horizontal distance. The error due to approximations is reduced by decreasing the sampling interval (dl) and $x_r(i)$ is the normalised i-th sampling interval. The study indicated that instrumentation selection is of key importance because any inherent errors on the sensor will compound to the total system error [25].

For off-road profilometer, ensuring the correct calibration is crucial, and one of the calibration methods is through creating a known excitation event[39]. The Can-Can profilometer validation was a good example validation through known excitation event. The validation was performed by profiling discreet concrete bumps on a concrete road at Gerotek vehicle testing facility[37]. A theoretical model of the bumps was constructed using information and dimensions supplied by the test facility, and the theoretical bumps were compared to the measured terrain bump. A deviation between the theoretical and actual bumps was expected due to the wear and tear on the concrete surface, and the results obtained by the profilometer proved that it could profile terrain up to an accuracy of 5mm.

The current study focuses on the validation of the LMT off-road profilometer measurement capabilities. Invalidating of the profilometer, acknowledgement is made of the fact that a profilometer has inherent accuracy errors, which include yaw, pitch, roll, aliasing and referencing measurements. While all this is true (errors influence the interpretation of road profile information), there are still several strategies to overcome these errors. This study introduces the entail steps in overcoming these errors. The first step is to quantify the level of precision required. Secondly, some tolerances $\lambda$ placed on the profile data requirements, which will take into account the application for which it the data is valid. Lastly, relevant aspects of the profile signal must be emphasized This is often expressed in wavebands of interest.
The problem is these errors result in inaccurate terrain profile. Accounting for the deviations and quantifying the accuracy of the device is thus the critical starting point in the validation of a profilometer. This study contributes by introducing a validation method for the off-road profiler, while current validation methods [39], [37], [27] are only focused on evaluating the accuracy alongside known excitation events. A more detailed study was conducted by Sang-Ho Lee and Sang-Hwa Goo in 2007 [14], but it only focused on developing a standardized measurement system for unpaved roads, and little emphasis was put on validating the accuracy of the device.

The method of calibration by excitation and validation against known obstacles are effective and thus in the current study this approach is incorporated to introduce a validation method which does not depend on known obstacles or terrains. For off-road profiling, the challenge is that off-road terrain is random and changes after every test thus validation through comparison of known obstacle or terrain is thus not possible. The presented method in this study is the laser sensor profile acquisition method developed to validate LMT profilometer off-road, which allows for independent terrain validation and ability to quantify the error found in each measurement.

Requirements for Off-road Profilometer

Literature review presented discusses the summary of roughness indices that are used to interpret profile information, and it further discusses the current systems and methods that are employed and research conducted by industry today in the field of terrain profiling. For each profiling system, the intended final application is the important factor that describes the accuracy level required.

The basic requirements for profile roughness measurements include mobility, rugged construction, the accuracy of measurement and usability of data [65]. Some tolerances must be placed on the level of precision, while the systematic bias of any kind must be discouraged. Secondly, emphasizing the relevant aspects of the profile signal, and ignoring the irrelevant aspects. Profile data limits are communicated as wavenumber (cycles/m) of interest. In practical terms, it means that aspect of profile that causes vehicle vibrations, commonly defined as the “roughness,” will be included in the judgment of agreement, and those that do not, such as the grade and texture, will be excluded. Table 5 depicts a requirement specification based on reviewed literature for defying profile requirements.
Table 5: Requirement Specification

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Measurement Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrain type</td>
<td>Off-road</td>
</tr>
<tr>
<td>Device Class</td>
<td>Class 2</td>
</tr>
<tr>
<td><strong>Maximum Longitudinal Sample Interval</strong></td>
<td><strong>25 &lt; and ≤ 150 (mm)</strong></td>
</tr>
<tr>
<td>Vertical Resolution</td>
<td><strong>2 ≥ and ≤ 4 (mm)</strong></td>
</tr>
<tr>
<td><strong>frequency range wave number</strong></td>
<td><strong>0.05-10 (cycles/m)</strong></td>
</tr>
<tr>
<td>Amplitude</td>
<td><strong>0.6&gt; and &lt;125 (mm)</strong></td>
</tr>
<tr>
<td>Period</td>
<td><strong>½ period</strong></td>
</tr>
<tr>
<td><strong>Frequency (Hz)</strong></td>
<td><strong>60Hz</strong></td>
</tr>
<tr>
<td><strong>IRI generally ranges(for off road)</strong></td>
<td><strong>4 to 12 (m/km)</strong></td>
</tr>
<tr>
<td>Speed</td>
<td><strong>Max : 50km/h</strong></td>
</tr>
</tbody>
</table>
3 Methodology

3.1 Profilometer Design

The following proposed method was followed in the verification of terrain measurement platform. Firstly, the repair of the LMT profilometer was conducted shown in Figure 3.1 is the state of the profilometer in 2014 before the research project was initiated. Secondly, profile acquisition method was developed. Lastly, an experimental evaluation test of the system was conducted.

![Figure 3.1: LMT profiler state in 2014](image)

Furthermore, research on current technologies such as a laser, LIDAR sensors, proximity sensor, tilts sensor and accelerometers will be conducted, and the best system based on the research will be suggested for the development of the terrain measurement platform.

3.1.1 Research Instrumentation

The LMT profilometer works by being towed by a vehicle over the desired terrain to be measured. The speed that the device is towed at was limited below 3km/h and was towed over a defined length of a road section. There were two measuring arms which span on each side of the device; this arm has measured the profile through making contact with the ground (see Figure 3.2). Sensors mounted on the instrument translated the measured profile to data points consisting of elevation, reference and longitudinal distance which were graphically reconstructed to represent the measured terrain.
3.1.2 Assembly of Profilometer

The test rig was assembled from four main sections (see Figure 3.3 and Table 6), which are: Measurement arms, Tow Hitch section, Front & rear wheel assembly and Trailing arm rails.
• Step 1 of assembly is to align the welded frame, rear wheel arm member and rear wheel arm member members labelled 6, 1 and 2 on the exploded view see Figure 3.3. The 21-inch wheels ladled number 7 will be consistently fixed to the device and will not be disassembled during the pre-test at CSIR.

• Step 2 of the assembly process is mounting the Trailing Arm Rail Right (4), Trailing Arm Rail Left (3) and the Tow Hitch Frame (11) onto the device.

• Step 3 is mounting the Assem 4_Measuring Arm Left (9), Assem 4_Measuring Arm Right (10) onto the device.

• Step for is mounting the instrumentation onto the apparatus.

Table 6: Profilometer Bill of Material

<table>
<thead>
<tr>
<th>ITEM NO</th>
<th>Part Number</th>
<th>DESCRIPTION</th>
<th>QTY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0313-005167-12-150</td>
<td>Rear Wheel Arm Member</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0313-005167-12-200</td>
<td>Rear Wheel Arm Member</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>0313-005167-12-250</td>
<td>Trailing Arm Rail Right</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>0313-005167-12-300</td>
<td>Trailing Arm Rail Left</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>UCP 210</td>
<td>UCP 210 Bearing</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>0313-005167-12-100</td>
<td>Welded Frame</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>STX200(Front Wheel)</td>
<td>Front Wheel STX200 Assembly</td>
<td>3</td>
</tr>
<tr>
<td>8</td>
<td>UCP 204</td>
<td>UCP 204 Bearing</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>0313-005167-12-350</td>
<td>Assem 4_Measuring Arm Left</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>0313-005167-12-400</td>
<td>Assem 4_Measuring Arm Right</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>0313-005167-12-50</td>
<td>Tow Hitch Frame</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>0313-005167-12-150</td>
<td>Structural Square Tubing with End Cap</td>
<td>1</td>
</tr>
</tbody>
</table>
3.1.3 Sensor Placement

The sensor placement was initially based on the original sensor position placement during the validation test carried out in 2005 and documented in the test report manual [20]. The original profilometer consisted of PT510 Ceresco’s, Tilt sensor and GPS unit as presented in Figure 3.4 indicates that the original sensors have placement position for these sensors. The sensor arrangement for evaluating alternative profiling measurement capabilities can be seen in Figure 3.5, Figure 3.6 and Table 7 for the location of the sensors.

![LMT displacement transducer placement](Image)

**Figure 3.4: LMT displacement transducer placement**

![Additional sensor mounting location](Image)

**Figure 3.5: Additional sensor mounting location**
Figure 3.6: Instrumentation placement
Table 7: Instrumentation Placement

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>LIDAR Sensor</td>
</tr>
<tr>
<td>B</td>
<td>VBOX III, 2 Axis Tilt sensor &amp; LEA-6 Module GPS</td>
</tr>
<tr>
<td>C</td>
<td>Accelerometer 10g &amp; 6g</td>
</tr>
<tr>
<td>D</td>
<td>Accelerometer 10g &amp; 6g</td>
</tr>
<tr>
<td>E</td>
<td>Optic displacement sensor 1</td>
</tr>
<tr>
<td>F</td>
<td>Ultrasonic Sensor 1</td>
</tr>
<tr>
<td>G</td>
<td>Laser Sensor 1</td>
</tr>
<tr>
<td>H</td>
<td>Laser Sensor 2</td>
</tr>
<tr>
<td>I</td>
<td>Optic displacement sensor 1</td>
</tr>
<tr>
<td>J</td>
<td>Ultrasonic Sensor 2</td>
</tr>
<tr>
<td>K</td>
<td>PT510 Celescos 1</td>
</tr>
<tr>
<td>L</td>
<td>PT510 Celescos 2</td>
</tr>
<tr>
<td>M</td>
<td>Single Axis Tilt sensor 1</td>
</tr>
<tr>
<td>N</td>
<td>Single Axis Tilt sensor 2</td>
</tr>
<tr>
<td>O</td>
<td>Accelerometer 10g &amp; 6g</td>
</tr>
</tbody>
</table>

3.1.4 Instrumentation Setup and Test

The following section details and describes all the instrumentation and equipment required to conduct the profilometer validation research.

**SoMat eDAQ-lite (Data Acquisition System)**

The SoMat eDAQ-Lite is a 16 GB stand-alone data acquisition system for testing in harshest environments as shown in Figure 3.7. 12VDC battery powers the eDAQ. It can perform a broad range of onboard data processing, triggering and data storage.
The eDAQ system is a 16-bit device used to convert and store the received voltages measurement from sensors into useful data. Sixteen channels of the eDAQ system will be used to collect the data from the following sensors: two laser scanners (see 0), four tilt sensor (see 0), two PT510 Celesclos displacement transducers (see0), six accelerometers (see 0), and two Laser Scanners (see 0). Storage space required is based on the expected frequency of 60Hz, and by applying Nyquist theorem, we get 600Hz. That implies we can select a sampling rate of 1kHz. The required storage space for each test has to be outlined below.

\[
\text{Storage space} = \frac{(1000+16+16)}{(1024+1024)} = 0.24 \text{ MB}
\] (3.1)

The sampling frequency will be set at 10kHz to improve the recode more points during measurement. That implies 2.44 MB of storage will be required. The eDAQ-Lite hardware that will be used for the test is made up of a central processor, serial bus, power supply module and four input bridges (see Table 8). The eDAQ-Lite TCE version 3.22 and the written program titled LMT Profilometer _Test_June_rev1.tce are used during the tests.

Table 8: Somat eDAQ Lite Used for Data Capturing

<table>
<thead>
<tr>
<th>IP Address</th>
<th>Description</th>
<th>Serial Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>192.168.100.103</td>
<td>Main processor</td>
<td>ELMPB.04-1010</td>
</tr>
<tr>
<td></td>
<td>MPB serial bus</td>
<td>ELMPB.04-1010</td>
</tr>
<tr>
<td></td>
<td>Power controller</td>
<td>ELPWR.03-0685</td>
</tr>
<tr>
<td></td>
<td>Bridge 1</td>
<td>ELBRG.02-0970</td>
</tr>
<tr>
<td></td>
<td>Bridge 2</td>
<td>ELBRG.02-0937</td>
</tr>
<tr>
<td></td>
<td>Bridge 3</td>
<td>ELBRG.02-0929</td>
</tr>
<tr>
<td></td>
<td>Bridge 4</td>
<td>ELBRG.03-4140</td>
</tr>
</tbody>
</table>
**Beagle Bone Black Rev C**

A Beagle Bone Black (BBB) Rev C device was used to record the data from LIDAR sensor (see Figure 3.8). The BBB system is a 10-bit device used to convert and store the received voltages measurement from sensors into useful data. This embedded computer device has been selected because the LIDAR sensor requires an RS-232 data output port and requires the installation of a Robot Operating System (ROS), which is Linux-based software. The embedded computer has Universal Asynchronous Receiver/Transmitter (UART) capabilities, which are ideal for RS-232 communication, and is a Linux-based computer.

![Figure 3.8: Beagle Bone Black Rev C](image)

The BBB functions the same as a PC only on a smaller scale making it an embedded PC. A Python script code is written which runs on the BBB PC. The code interprets the sensor inputs and consistently logs data from each sensor connected to it. The 5 GPIO pins of BBB system was used to collect the data from the following sensors: GPS, Hall Effect Sensor, 2 Ultrasonic Sensor.

The sensors are connected to the BBB, and they continuously log data and save it to a text file. Storage space required was based on the expected frequency of 60Hz, and by applying Nyquist theorem, we get 600Hz, which implies we can select a sampling rate of 1kHz. The required storage space for each test was calculated as outlined below.

$$\text{Storage space} = \frac{(1000\cdot 9\cdot 10)}{(1024\cdot 1024)} = 0.086\text{MB}$$ (3.2)

The sampling frequency was set at 10kHz so as collect more data points during measurement, and this implied 0.86MB of storage was required.
**Light Detection and Ranging (LIDAR) Sensor**

A SICK LMS-211 LIDAR sensor as shown in Figure 3.9 is capable of measurements of up to 8m vertical radius at a coverage angle of 180° at low power consumptions of 20W (see Figure 3.10). The sick laser scanner is a non-contact measurement system, which communicates via a serial protocol (RS-232). The LIDAR system communicates directly with a personal computer (PC) because it uses serial communication. Frequency ranges 10 to 150Hz with an amplitude of 0.35mm. In the present study, the sensor was mounted in front of the profilometer facing towards the ground during measurement.

![Figure 3.9: SICK LIDAR sensor](image)

![Figure 3.10: LIDAR scanning angle](image)

**Laser Scanner**

A laser scanner measures the surface profile with the use of reflecting a light beam at an angle on the target surface. For the evaluation test, two ML7 400 model laser scanners are used to report two dimensions (2D) data which represent a true profile (see Figure 3.11). The sensors were positioned 480mm above the ground as defined by the MEL model beginning range for measurement, and they have a sampling frequency of 54kHz. The suggested supply power requirement is 12 to 24VDC. The dimensions of the sensor are 187 by 50mm with a thickness of 42mm weighing 850g.
The ML7 was connected to an M7-series electronic unit used for RS 232 interface and setting default output settings required by the sensor. The unit sets the RS 232 baud rate to 9600 baud and selecting the output frequency between 0.015 and 10kHz and to additionally select the sensor has triggered a slave or master sensor. The expected output is distance measurement. The output from the sensor is an optional 10V signal, which can connect directly to the eDAQ-lite and the suggested output is measured using a voltage divider circuit, which divides the voltage down to 5V to protect the eDAQ-lite input port. The sensor also has an additional option to Output 4 to 20mA signal via RS 232. The measurement beam has a diameter of 4mm, and its light beam is projected vertically see Figure 3.12.

The ML7 was calibrated by conducting an empirical experiment where the sensor response voltage was recorded along with the distance measured from the ground surface. The results of the calibration were plotted in a graph format as depicted in Figure 3.13 and Figure 3.14. The graph gave a linear response, and a linear equation was calculated from the chart which stated that for $y$ voltage the corresponding displacement is given by $x$. 
Based on Celesco’s original string pot design dating back to the late 1960’s [66], the PT510 is considered a standard throughout the years for literally thousands of applications including aircraft structural testing to hydraulic cylinder control [67]. The PT510 provides a regulated voltage feedback signal linearly proportional to the position of its travelling stainless steel measuring cable. Output signal options include 0-5 and 0-10VDC. The PT510 is used as a displacement sensor for measuring profile elevation, and the device is mounted on the profilometer arms. This device was the original device that was used when the in the original LMT profilometer design as shown in Figure 3.15.

**PT510 Celescos**

![PT510 Calibration Graphs]

**Figure 3.13: M17 1106-999A calibration**

**Figure 3.14: M17 0108-402A calibration**

![PT510 Device Image]

**Figure 3.15: PT510 Celescos [67]**
The PT510 string potentiometer was calibrated by conducting an empirical experiment where the sensor response voltage was recorded along with the displacement that the string pot travelled. The results of the calibration were plotted in a graph format as depicted in Figure 3.16 and Figure 3.17. The graph gave a linear response, and a linear equation was calculated from the graph which stated that for y voltage the corresponding displacement is given by x.

![String pot 1 graph](image1)

Figure 3.16: String potentiometer 1 calibration

![String pot 3 graph](image2)

Figure 3.17: String potentiometer 3 calibration

**Global Positioning System (GPS)**

The Adafruit Ultimate GPS offers standalone GPS units able to operate using an internal or optional external antenna. The GPS is capable of tracking 22 Satellites and searching 66 Satellites, while the position accuracy of the GPS is 1.8m with velocity accuracy of 0.1m/s. The update rate is 1Hz to the 10kHz frequency range. The device communicates directly with a PC via UART serial interface. The voltage requirement of the device is 5VDC with a 20mA current draw (see Error! Reference source not found.) [68].

45
The expected output of the GPS module was logged and data collected using a BBB PC. The National Electrical Manufacturers Association (NEMA) standard is used to define all GPS output data [70]. The output was in the form of NEMA sentence and was converted to strings. Python code was used to split the comma separated string text into groups. Once that was accomplished, the output was displayed in detail certain portions of those groups to screen or data script. The final output data consist of all the required information satellite information, time, longitudinal distance; velocity knots, heading vertical speed and event time (see Figure 3.19 Figure 3.20).

![GPS NEMA string output data](image)

**Tilt Sensors**

The tilt sensors used are part of the CXTA series, which consist of the single axis and double axis tilt sensors. The CXTA series sensors use acceleration sensing element with a DC response to measure inclination about gravity (see Figure 3.21). For the evaluation test, three single axis and one dual axis tilt sensors were selected. The sensors have a bandwidth of 50Hz and a sensitivity of 35mV/ ± 2° with a maximum sensed the angle of ± 75°. The normal voltage required powering the sensor is between the range of 6-39VDC [71],[72].
Tilt sensor expected data output is a voltage taking into account the sensitivity of the sensor. The output voltage will be translated to an angle (see Figure 3.22).

The CTXA angle was calibrated by conducting an empirical experiment where the sensor response voltage was recorded along with the measured angle. The results of the calibration were plotted in a graph format as depicted by. A trend line was plotted on the graph to calculate an equation that represents the relationship between voltage and the measured angle Figure 3.23. Furthermore using knowledge observed from the line response graph the Somat TCE software was used to calibrate the angle sensor connected to the eDAQ to compute the measured angle in real time see Figure 3.24.
Proximity measurement and detection will be focused on the object of interest, for the elevation test, measurement is focused on sensing the motion of the measurement arms [25]. Ultrasonic sensor selected for proximity measurement (see Figure 3.25) which transmit a pilot signal and receive a reflected signal to determine the distance measured.

**Specifications Ultrasonic Sensor**

- Power Supply: 5VDC
- Effectual Angle: < 30 degrees
- Ranging Distance: 2cm to 500 cm
- Resolution: 1cm
- Ultrasonic Frequency: 40kHz
Ultrasonic waves emitted by the transducer at time 0 and reflected by an object are received back into the transducer. This whole process describes how an echo signal is transmitted. The next pulse wave can be transmitted when the echo is faded away or is received back. The ultrasonic sensor will switch to receive mode after transmitting an echo. The time elapsed between emitting and receiving recommended cycle period should not be less than 50ms. The ultrasonic module has an output of eight 40kHz signals, and the distance measured is proportional to the echo pulse width of the signal (see Figure 3.26) [74].

![Figure 3.26: Ultrasonic waves emitted by the transducer][74]

**Ultrasonic Sensor Calibration**

The HC-SR04 has four pins: VCC and GND (which supplies power), a pulse signal is initiated on the Trig pin (which initiates a pulse signal), controlled by 3.3V, and the Echo pin which measures the result with the maximum output of 5V. So to use it with BBB GPIO we need to bring it down to around 3.3V. A voltage divider circuit was selected and set to half the output voltage potential over two resistors, connected in series, as illustrated Figure 3.27, to regulate the output signal.

![Figure 3.27: Voltage divider circuit][75]
The GPIO pin is driven by a minimum voltage of 2.5V to read positive, so 3V was sufficient output as required by the BBB, to achieve this voltage output R1 = 220Ω and R2 = 330Ω [75]. The ultrasonic sensor test steps up is shown in Figure 3.28 which consists of the 30cm ruler, ultrasonic sensor HC-SR04, and a BBB device.

![Figure 3.28: Ultrasonic sensor test setup](image)

The experiment results are presented below in Figure 3.29 and Figure 3.30 where the sensor measured an obstacle placed at 45mm. The results show that the sensor was scattering all over the place and displayed values that are not correct which represent outliers. Applying an averaging filter on the data made a difference, however, furthermore filtering of outliers is required to filter the data.

![Figure 3.29: Ultrasonic test 1 results](image)

![Figure 3.30: Ultrasonic test 2 results](image)
**Accelerometer**

Off terrain road environment where the LMT profilometer is required to function is known for inducing vibration, and an accelerometer has been selected to sense this vibration. They expect full range acceleration expected vibration had been calculated to be 10g. To capture for both the full spectrum and expected wave a 10g accelerometer model 3028-010 (see Figure 3.31) had been selected, and a 3-axis 1.5g model MMA7361L accelerometer (see Figure 3.35) has been selected to account for the expected acceleration as based on literature. The Model 3028-010 accelerometer has a sensitivity of 4.19mV/g at 100Hz operating at 24°C and requires 5vDC supply.

![Model 3028-010 accelerometer](image)

**Figure 3.31: Model 3028-010 accelerometer**

Calibration of the Accelerometer was accomplished through using the Somat TCE software used to control the communication between the eDAQ and the hardware. A calibration certificate was provided with the three accelerometers used during testing. The calibration of each accelerometer presented in Table 9. Using the data provided in by the sensor calibration certificate, the TCE software with required data to be able to output the g value about the measured acceleration while allowing depictive graphic representation when calibrating the expected response from each sensor as seen in Figure 3.32, Figure 3.33 and Figure 3.34.

**Table 9: Accelerometer Calibration**

<table>
<thead>
<tr>
<th>Accelerometer Model number</th>
<th>Input Resistance(kΩ)</th>
<th>Zero Offset (mV)</th>
<th>Sensitivity (mv/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1796-011</td>
<td>3.54</td>
<td>3.74</td>
<td>4.05</td>
</tr>
<tr>
<td>1796-019</td>
<td>3.45</td>
<td>-4.52</td>
<td>4.88</td>
</tr>
<tr>
<td>1796-021</td>
<td>3.42</td>
<td>-8.86</td>
<td>4.80</td>
</tr>
</tbody>
</table>
Figure 3.32: Calibration left frame accelerometer

Figure 3.33: Calibration right frame accelerometer
The MMA7361L model accelerometer has a sensitivity of 800mV/g at the configurable frequency with an external capacitor external filter standard at 550Hz operating at -40 to 85°C and requires 3.3VDC supply.

MMA7361L Accelerometer gives an output voltage between 0-3.3V and because BBB analogue read pins are 1.8V tolerant, using a resistor voltage divider on each of the accelerometer outputs axes. This provides a range of 0-1.65V to be read on BBB analogue read pins. Due to the output impedance of the ADXL335 being ~32kOhms, a low resistor value for the voltage divider is recommended (between 500 Ohms- 1k Ohms) [77]. Converting the output voltage with simple math is required to interpret the measured acceleration in G’s. The output is a linear response obtained by using the following equation of a straight line because the output voltage is proportional to acceleration as seen in Figure 3.36.
Hall Effect Sensor

A Hall Effect 3144 Hall sensor selected for distance and speed measurement (see Figure 3.37). The hall effect senses a magnetic field, and due to this, it is ideal for environments where dust is involved and where there are moving parts. The sensor requires 5vDc with the capability of sensing unlimited magnetic flux density, which means circuit, will not be damaged by sensing magnetic overdrive [78]. The sensor has an operating temperature range of -40 to 85°C. A Hall Effect is a transducer that varies its output voltage in response to a magnetic field. Hall effects application span from proximity switching, positioning, speed detection, and current sensing applications [79],[80]. In this the profile measurement application, the sensor is used for speed detection and a mathematical formula issued to translate the rate to the longitudinal distance covered.

The hall sensor is connected close to the front wheel and measures the RPM of the rotating wheel by sensing the magnet attached to the wheel [81]. The VCC, GND, and Data (Output) of the sensor are connected to the BBB, while the data output is connected to one of the GPIO pins, and VCC connected
to the +5V and GND to ground. The magnet passes the sensor multiple times to produce a pulse signal output. The signal is a fluctuation of analogue voltage reading from high to low or from 3.1V (approximately) to 0V, and the changes in the state of the GPIO is calculated to give an output variable called pulse. The time taken for a wheel to make a complete rotation cycle defines the value of the first pulse, and the time taken is denoted by the variable called elapse time with a unit of second. Elapse variable is used to calculate the RPM speed variable based on the ever changing elapse timing [82]. Further calculation of the longitudinal distance travelled corresponds to the elapsed time.

Figure 3.38: A remote reading location of hall effect sensor[83]
3.2 Profile Acquisition

The theoretical model prescribed in the LMT profilometer operating manual used to compute the road profile is given by the following equation:

\[
Left_{\text{profile}} = Left_{\text{profile}} - \frac{\text{Track Width}}{2} \cdot \sin(Body \ Roll)
\]  

\[
Right_{\text{profile}} = Right_{\text{profile}} - \frac{\text{Track Width}}{2} \cdot \sin(Body \ Roll)
\]

Descriptively this can be seen in Figure 3.39 where a two-dimensional drawing overview of the profilometer is shown explaining the measurement equation of the profilometer. Where \(y_L\) represents the left profile and track width the distance between the two measurement arms, while body roll measured at point A on the frame. Furthermore, the measured profile angle is represented by \(\theta_p\) and \(\omega_f\) represents the speed and distance traveled.

![Figure 3.39: LMT profilometer measurement model](image)

The LMT profilometer measurement model only makes use of the two measurements the changing in height displacement measured by the potentiometer sensor and the tilt sensor mounted on top of the frame to measure the pitch and roll angle. This model fails to use all the acquired data to derive a profile output, and the current model would result in an extremely filtered profile because measurements would are derived from the frame motion when driving over a given terrain thus resulting because of the measurement based on the motorcycle wheel diameter. This profile acquisition section presented alternative methods both from literature and derived from the available instrumentation mounted on the profilometer to make use of sensor fusion technics that would highly improve the terrain profile quality to determine the validity of the profilometer and detail the full operational potential of the profilometer.
3.2.1 Potentiometer Sensor Profile Acquisition

The theory of operation of the potentiometer sensor is illustrated in Figure 3.40. The figure defines how the desired surface profile can be acquired using the bottom mounted potentiometer (pot). As sensor placement section 3.1.3 the bottom pot measures length \( l_n \) when driving the instrument over an obstacle.

![Figure 3.40: Potentiometer profile acquisition model diagram](image)

Length \( l_n \) forms part of the trigonometric triangle with angle \( \beta_n \) and where \( a \) is the distance from the main joint centre point to the centre back wheel of the measurement arm. During motion angle \( \beta_n \) is seen to be the summation of the initial angle \( \beta_i \) taken at the starting point before profiling and angle \( \alpha_n \) formed due to the \( \Delta l \) of \( l_n \) at a point in time. The change in length \( \Delta l \) is calculated by subtracting starting point length \( l_i \) of the string pot form measured \( l_n \) during motion. Mathematically described as follows:

\[
l_n = b \sin \beta_n \quad (3.5)
\]

\[
b = \sqrt{a^2 + l_n^2} \quad (3.6)
\]

\[
\beta_n = \tan^{-1} \left( \frac{a}{b} \right) \quad (3.7)
\]

\[
\beta_n = \beta_i + \alpha_n \quad (3.8)
\]

\[
\alpha_n = \beta_n - \beta_i \quad (3.9)
\]

The rule of opposite angles state that opposite angles are equal which implies that the surfaces profile angle \( \theta \) is equal to \( \alpha_n \).
3.2.2 Surface Contact Profile Acquisition

The slope integration method introduces a discrete equation taken from an integration equation where the ground of increment $\Delta x$ and elevation is computed for constant increments $\Delta s$ to give the output profile.

\[
x_i = \sum_0^i \Delta x_i \quad (3.10)
\]
\[
y_i = \sum_0^i \Delta y_i \quad (3.11)
\]

The slope integration method is implanted in this study and is further simplified to allow ease of computation and similar notation for this study is adopted for reference to similar measurements made in the study and Figure 3.42 further illustrates the measurement-wheels profile acquisition theory. The angle measurements are acquired using a Tilt angle sensor while the distance travelled measured using a Hall Effect sensor.

\[
\Delta x_i = \Delta s (\cos \theta)_i \quad (3.12)
\]
\[
\Delta y_i = \Delta s (\sin \theta)_i \quad (3.13)
\]
\[
dx = x_{[n]} - x_{[n-1]} \quad (3.14)
\]
\[
y = y_0 + \sum_{i=1}^n \sin \theta_n (x_{[n]} - x_{[n-1]}) \quad (3.15)
\]
\[
x = \sum_{i=1}^n \cos \theta_n (x_{[n]} - x_{[n-1]}) \quad (3.16)
\]
3.2.3 Laser Sensor Profile Acquisition

The profilometer wheel positions which is the change in distance travelled is denoted by $x_{1:t}$ while, the profile is donated by $\rho$ the change states when the profilometer moves over time ($t$). The geological profile of the land surface is taken before its state changes over time usually over few weeks or due to different seasons in the year. The profile will more likely not change faster than $t$ and because of this fact, it is assumed to be time-invariant. The profile is set of feature $\rho_i$ and $\rho_i \in \rho$ and Figure 3.42 further illustrates the laser sensor profile acquisition theory.

![Figure 3.42: Laser sensor data path profile acquisition model diagram](image)

When acquiring an environment profile, the profilometer takes measurements data points at time $t$ which are denoted by $Z_t$. The height of the profile is computed from measured data points using $x_t$ and for a group of consecutive heights is denoted by $x_{1:t}$ the measurement function $h$ estimates geological profile based on the pose $\theta_t$ and height $x_t$.

$$Z_t = h(\theta_t, x_t) + E_t$$  \hfill (3.17)

$$h(\theta_t, x_t) = x_t \sin \theta_t$$  \hfill (3.18)

$$Z_t = x_t \sin \theta_t + E_t$$  \hfill (3.19)

$E_t$ is a g the measurement noise with zero mean and covariance $\theta_t$ and $\rho$ is the profile future approximated by the profilometer at the $t$. Put differently we have:

$$\bar{z} = Z_t - h(\theta_t, x_t)$$  \hfill (3.20)

$$\rho(Z_t|\theta_t, x_t) = \text{const} * \exp \left( -\frac{1}{2} (Z)^T \theta^{-1}(Z) \right)$$  \hfill (3.21)
Getting as close to the original value which best represents the observed measurement is achieved by taking a signal measurement multiplied it but its noise. Taking signal data from laser measurement and the pose, while bearing in account the noise with the measurement function $Q$ which is the covariance of the measurement noise archives the desired result.

$$(Z_t - h(\theta_t, x_t))^T Q^{-1}((Z_t) - h(\theta_t, x_t))$$

Profile data is computed using the following equation that sums all constraints to profile a surface in the form.

$$J_{profile} = \sum_t (Z_t - h(\theta_t, x_t))^T Q^{-1}((Z_t) - h(\theta_t, x_t))$$

$$J_{profile} = \sum_t ((x_t \sin \theta_t + E_t) - x_t \sin \theta_t)^T Q^{-1}((x_t \sin \theta_t + E_t) - x_t \sin \theta_t)$$
3.3 Profile Modelling

After taking into account all the evaluation and test manuals documented regarding the LMT profilometer, an ultimate validation test was required to determine the accuracy of the device and consolidate all findings relating to the instrument before commencing on the recommended redesign of the profiler.

The purpose of this study was to validate the repaired LMT profilometer. The first step was to quantify the level of precision required for off-road profilometer. Secondly fix the profilometer to a functional state, which would allow for future experiments and testing of the device. Lastly validate the error and accuracy level which takes into account the application for which the profilometer is valid, while relevant aspects of the profile data are presented according to the ISO 8608: 1995-09-01 standard [84].

The study was achieved by dividing focus into three profiling methods. These methods included surface contact measurement wheels and non-contact laser measurement. The methods were evaluated as part of a sensor network where multiple sensors were coupled together to give a similar outcome. All the findings of each method were compared, and the best method was recommended. The approach for executing the verification study is divided into three folds namely: the calibration of test equipment, using a sensor network made up of displacement sensors, laser scanner, and LIDAR fitted on to the existing profilometer platform.

Two test were conducted to achieve the object of the project these tests are namely an obstacle test and an off-road test. Firstly a Solid Work model of know obstacle was created. The obstacle test is a discreet experiment where the obstacles dimension is known which allows for validation against an imperial simulation indoor to calculate the error in the system while determining the accuracy of the platform. The off-road test represents the random excitation environment for which the profilometer has been designed to operate. The off-road test results are compared against the sensor network fitted on the platform, and a conclusion is discussed based on the data comparison.

During measurement, there was a GPS system installed on to the LMT device. The GPS acted, as a relative measurement tool which provided the elevation of the moving profilometer about a fixed GPS base station. The GPS expected data output contains location information, event time, longitudinal distance, speed or velocity and the elevation of the profile surface. Height about the reference will be measured using displacement Sensors, laser scanner, LIDAR Sensor and PT510 Celescos. Additionally, the Longitudinal distance was measured using a Hall Effect sensor which in turn will also be used in determining the speed of the measurement device. The measured data is analyzed using Matlab™ to extract the desired components of true profile. The outcome of the analysis includes a graphical representation of the elevation vs. longitudinal distance.
The terrain data consisting of the components of the actual profile required as an input into SAAMM and is accessible through the ArcGIS interface where it may be viewed or updated [2]. New road profiles can alternatively be defined through the ArcGIS interface to meet essential needs. The profiles are interfaced using Digital Evaluation Map (DEM) created with ArcGIS tools. Data contained within a DEM map proved information to describe the vegetation, soil, and relief of each area in detail. Mobility models require additional quantitative data added to the DEM described by terrain data measurements regarding roughness to help relate the description of sectors to quantifiable units for the mobility model [19].

The mobility model in question SAAMM has two main outputs, which is the percentage of the SAACTC that can be negotiated by a vehicle with specific automotive characteristics, as well as the average speed attainable. Moreover, analysis can be performed using the terrain data such as negotiability predictions, mobility descriptors such as a vehicle speed map and vehicle speed profile. The average speed predictions are time domain simulations and performed for realistic missions or missions defined by the user. Since the simulation is stochastic, it is possible to assign a confidence level to the average speed predictions [2].

\[3.2 \text{ Summary}\]

The methodology starts by giving the background including the original state of the profilometer before the validation test and then proceeds to detail the profilometer design with all repair work made to the instrument. Moreover, presented in this chapter is the theory of operation of the profilometer along with the profile acquisition methods used to compute the road profile and to validate the profilometer. The methodology sections culminate with a detailed discussion about the approaches used to validating the profilometer and in conducting the experiment test.
4 Experiments

4.1 Experimental Setup

4.1.1 Obstacle test1

A pre-evaluation test was done at CSIR to verify the correct functionality of the test instrumentation and test items. The following evaluations were made during the pre-test: functionality of all the sensors on the LMT profilometer and the overall data based on the requirements specification. The test conducted on a discrete obstacle which is a ramp made up of the wooden pallet (125mm high and 815mm long) and a rectangular wooden plank (798mm by 800mm) placed at 11°. Using a known obstacle with fixed dimension for the pre-evaluation test allows a simulated model to be made which acts as a reference for comparison to study the operation of the profilometer.

![Figure 4.1: Obstacle test1](image)

The simulation model illustrated in Figure 4.2 is created using SolidWorks motion study and making an empirical observation of the profilometer as it moves over the obstacle. In both the test and the simulation the measurement arm observation was made measuring the arm angle, elevation of the arm platform with relation to measurement wheels, elevation of the arm relative to the profilometer frame and the distance travelled. In the simulation, furthermore, data was measured such as the profile angle and change in distance during motion.
4.1.2 Obstacle Test 2

The second evaluation test was based on the slope integration profiling method to interpret profile elevation, and this approach was selected based on the current mode of operation of the LMT profilometer. Furthermore, the laser sensor profile acquisition 3.2.3 model is used to validate the profile acquired from the measurement-wheels. The sensors selected for this test were: Two Tilt sensors, two accelerometers, and a laser sensor. The test conducted as seen in Figure 4.3 consist of two pallets used as a ramp, where the first pallet was 125mm high and the second was 100mm total length of the ramp was 5m. The laser sensor was required to verify the data of the measurement arm and placed ahead on the measurement arm by 800mm.
The measurement arm sensors selected depicted in Figure 4.4 for this test is one tilt sensor positioned on top of the arm and two accelerometers positioned perpendicularly from each other. The accelerometer output is used to calculate the same angle measured by the tilt sensor, which would allow for a comparative study of the two sensors. Furthermore, the trigger of the test is position close to the obstacle platform, which means when the wheels make the first contact with the obstacle data acquisition eDAQ is digital signalled to start data recording.

![Figure 4.4: Obstacle test2 measurement arm sensor placement](image)

Figure 4.4: Obstacle test2 measurement arm sensor placement

Figure 4.5 depicts the ML7 400 sensor positioned 800mm ahead of the measurement-wheels.

![Figure 4.5: ML7 400-sensor placement](image)

Figure 4.5: ML7 400-sensor placement

The simulation model illustrated in Figure 4.6 created using SolidWorks motion study and making an empirical observation of the profilometer as it moves over the obstacle. In the simulation, the profilometer measurement arm records the elevation travelled over the obstacle.
4.1.3 Off-road Test

An off-road test experiment conducted at the CSIR to verify the function of the profilometer in its operational environment. The profilometer depicted in Figure 4.7 used for this trial consisted of an eDAQ-lite, BBB, SICK LMS-211 LIDAR sensor, four PT5100 Celescos, GPS, three tilt sensors, two Ultrasonic sensors, five accelerometers and a Hall Effect sensor. A Toyota quantum is selected to tow the profilometer towed at low speeds in the first gear without accelerating the vehicle.

The off-road course illustrated in red in Figure 4.8 situated at the CSIR Pretoria campus behind building 45. The off-road track span over 100m starts in front of building 46 as depicted in Figure 4.9 and endpoint as shown in Figure 4.10 situated on the side of the Department Of Science And Technology building.
Figure 4.8: Off-road 100m path labelled in red

Figure 4.9: The starting point of the off-road test

Figure 4.10: Endpoint of off-road test
4.2 Experimental Results

4.2.1 Obstacle Test 1 Results

The Top string potentiometer situated in the location labelled as indicated in Figure 4.11. The potentiometer is responsible for measuring the elevation of the arm in relation to the profilometer frame. Elevations in the obstacle test 1 experiment si-units are in millimetres (mm) due to the diminutive size of obstacle used and to allow for clarity when referring to the data. There was three experimental test alteration of the above test conducted, and each is contacting four repetitions. Unfortunately, multiple challenges were faced based on this initial instrumentation test only one of the three test provided satisfactory results which contained both distances travel, angle displacement height and acceleration. Errors occurred due to the drop off point at the end of the obstacle that resulted in communication lost and several sensor log data lost during measurement. Test1 served as an instrumentation configuration and calibration experiment test where errors due to connection, sampling rate, and sensor calibration where solved despite the challenges faced.

![Figure 4.11: Top string potentiometer](image)

The sensor makes it measurement in compression, meaning when it climbs the 10° ramp obstacle the original length at point A reduces to length x and vice versa when stepping down from an obstacle. The figure below gives a description of the simulation data as the profilometer climbs over and the obstacle depicted in Figure 4.12. In the simulation data graph, note that at the start of motion the sensor records the high of the obstacle at 478 mm, while the stop position is on top of the ramp at an elevation of 310.54mm see Figure 4.12. Figure 4.13 depicts the measured data from the top potentiometer.
Figure 4.12: Top String pot simulation data elevation vs. distance travelled

Figure 4.13: Top string pot measured data

Figure 4.14 depicts the bottom string potentiometer location labelled as B. The potentiometer is responsible for measuring the elevation of the measurement-wheels with relation to the profilometer arm as shown in the.
Figure 4.14: Bottom string potentiometer

The lower sensor makes measurements in tension, meaning when it climbs an obstacle the elevation at point B will increases to height x and vaso verso when stepping down from an obstacle. Figure 4.15 below gives a description of the simulation expected data as the profilometer climes over and the obstacle. Depicted in Figure 4.16 is the measured data from the experiment test.

![Elevation vs Distance travelled](image)

Figure 4.15: Bottom string potentiometer expected data
As stated above the distance travelled increment $\Delta x_n$ measured in the simulation and the profile angle $\theta_n$. The simulation data is analyzed and computed using the slope integration method for constant increments total distance travelled $x$ to give the output profile elevation. The results from the simulation measurements in Figure 4.17 depict the profile along with potentiometer-simulated results elevation profile plotted against the obstacle dimensions. The motion increment $\Delta x_n$ was taken to be 125mm to reduce computation time. Moreover, this change in distance was used when developing the theoretical model in the methodology and provided a point of comparison. Analyzing the RMS error for the surface profile as an elevation in (mm) determines the difference between the simulated data and current obstacle profile. The computed RMS error for the Top potentiometer data as seen in Figure 4.17 produces an inaccuracy of 33,887mm means that the simulated profile is 33,887 away from representing the obstacle profile. The simulated profile using slope integration method produces an RMS error of 32.616mm.

Figure 4.16: Bottom string potentiometer measured data
Surface change in distance travelled of increment $\Delta x_n$ data measured by the Hall Effect sensor and $\theta_n$ data measured by the tilt sensor angle are computed using the slope integration method for constant increments total distance travelled $x$ to give the output profile elevation. The results from the test along with the simulation are graphically depicted in Figure 4.18. Graphical presented on Figure 4.18 is test 1 and test 2 initial evaluation test of the profilometer. The calculated RMS error for test 1 is 5.3mm shifted away from the true profile, while for test 2 the RMS error is 8.1m away from obstacle true profile. Presented in Figure 4.19 are the potentiometer profile Data from test 1 and 2 including the predicted simulation profile.
The string potentiometer on placed on top of the measurement arm as a displacement device mastering the height. The reference offset which is the initial point before each test needs to be measured and subtracted from the measured data to get the actual profile data as depicted seen in Figure 4.19. The computed RMS error of the potentiometer data compared to obstacle profile are recorded as follows: for Test 1 RMS error of 67.77mm, Test 2 error of 41.81mm and simulation produced an error of 27.86mm.

![Potentiometer Profile Data](image)

**Figure 4.19: Bottom string potentiometer measured data**

### 4.2.2 Obstacle Test 2 Results

As stated in the experimental set up the distance travelled increment $\Delta x_n$ moreover, the profile angle $\theta_n$ Simulation data are analyzed and computed using the slope integration method to give the output profile elevation. The motion increment $\Delta x_n$ was set to half the wheel diameter 100mm. The increment value states that data is recorded at every wheel radius rotation and is selected as a reasonable value to reduce computation. The results from the simulation measurements are depicted in Figure 4.20 the profile results elevation profile plotted against the obstacle dimensions. Computed results of the RMS error to study the deviation between simulation and obstacle dimensions state that the simulation RMS error is 11.739mm.
The Laser Sensor Profile Acquisition 3.2.3 model is used to calculate the elevation profile from the acquired laser sensor data. Figure 4.21 illustrates the data acquired from the laser sensor it as stated in the experiments set up that the laser sensor is placed 800mm ahead of the measurements wheels which are used to trigger the measurement.
The surface change in distance travelled of increment $\Delta x_n$ data measured by the Hall Effect sensor and $\theta_n$. Data measured by the tilt sensor angle computed for constant increments total distance travelled $x$ to give the output profile elevation. Figure 4.22 graphically depicted results from the second obstacle test experiment. The obstacle Test2 data is furthermore graphically plotted against simulation test Figure 4.20 and laser obstacle profile Figure 4.21.

![Figure 4.22: Obstacle test 2](image)

![Figure 4.23: Obstacle test2 data plotted with laser obstacle profile](image)
Figure 4.24: Simulation data plotted with obstacle test2 data
5 Remarks and Conclusion

The purpose of this study was to validate the operation of the off-road LMT profilometer. The study was achieved by dividing focusing on three key approaches. The first step was to quantify the level of precision required for off-road profilometer. Secondly, fix the profilometer to a functional state, which would allow for future experiments and testing of the device. Lastly, conduct evaluation test based on profiling theory of operation to evaluate the error and accuracy level, which takes into account the application for which the profilometer is valid.

The result presented in 4.2.1 obstacle test showed that the displacement $y_t$ measured by the potentiometer experiment has an average RMS an error of 55 mm shifted away from the actual profile, which is 37% of the highest evaluation of the obstacle. The potentiometer simulation produced unsatisfactory results overall as seen in Figure 4.17 were an average RMS error of 23% is calculated from the results. It is recommended that an alternative profile model equation is used or developed for computing profile based on the results.

To fully take into account, the capability of the current profilometer various analytical methods were implemented such as the slope integration method and the laser sensor profile acquisition model developed for validating the profilometer. These methods use different technics such as surface contact measurement wheels and non-contact laser measurement. The methods were evaluated as part of a sensor network where multiple sensors were coupled to give a similar outcome as seen in the result in Chapter 4.

Through simulation, it was shown that the applying the slope integration method for profile computation produces an RMS error of 7.3%. Application of this approach would significantly improve the LMT profilometer. This study contributes by firstly validating the LMT profilometer and secondly by introducing a validation method for off-road profilometers. The above computation reduced the expected error from 67% as indicated in the literature of the LMT profilometer by 59.7%, which is an improvement to the current system. The developed validation method does not need prior knowledge of terrain being measured to offer a comparison and thus set this study apart from other researchers. Providing a profiler with the capability to be able to determine the deviation in measurements and keep track of the accuracy of the instrument throughout the measurement process. This process account offers the ability to off-road profiles to be able to account for aliasing error in measurement.
Further, this chapter has examined the theory of operation of the LMT profilometer and found that based on its current profile computation equation it theoretical inaccurate because of it computers highly filtered profile average. This basic filtering of the profile is because with the frame is acting as the measurement plane and the reference, while the motorcycle wheels determine the amplitude of the profile or as referred to in the basic function method plain height. Implementing a different computation algorithm as suggested reduces the expected error of the device by over 50% and in theory, allows the LMT profilometer to have a minimum profiling limit of 10mm shift from the measured profile.

After the validation test, findings future work would be to mechanical upgrade to a device that dose not deepened on the motorcycle wheels to make measurements as demonstrated and the strength the steel frame. The study of off-road profiling is suggested to be continued to postdoctoral level where the focus would be expanding on a terrain predictive profile method, which can be used to determine measurement accuracy of any off-road profiler.
6 Bibliography


