UNIVERSITI PUTRA MALAYSIA

SCALE-INVARIANT AND ADAPTIVE-SEARCH TEMPLATE MATCHING FOR MONOCULAR VISUAL ODOMETRY IN LOW-TEXTURED ENVIRONMENT

MOHAMMAD O. A. AQEL

FK 2016 6

SCALE-INVARIANT AND ADAPTIVE-SEARCH TEMPLATE MATCHING FOR MONOCULAR VISUAL ODOMETRY IN LOW-TEXTURED ENVIRONMENT

By

MOHAMMAD O. A. AQEL

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

May 2016

DEDICATIONS

I would like to dedicate this thesis to:
my lovely parents,
my beloved wife and children
my brothers and sisters,
my friends,
and to my beloved country (Palestine).

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

SCALE-INVARIANT AND ADAPTIVE-SEARCH TEMPLATE MATCHING FOR MONOCULAR VISUAL ODOMETRY IN LOW-TEXTURED ENVIRONMENT

By

MOHAMMAD O. A. AQEL

May 2016

Chairman : Professor Mohammad Hamiruce Marhaban, PhD
Faculty : Engineering

The most important task for any autonomous mobile vehicle is the reliable estimation of its position over time. Visual odometry (VO) is a localization technique that estimates the position of a robot using only the stream of images acquired from a camera. A monocular VO system that uses a single downward-facing camera to estimate the relative position of a ground car-like vehicle at low-textured environments is presented in this thesis. In general, the main limitations of existing VO systems are related to computational cost and light and imaging conditions such as sunlight, shadows, image blur, and image scale variations.

Fluctuations in camera height from the ground when driving on an uneven terrain can lead to variations in image scale and, in turn, affect the accuracy of vehicle position estimation. Therefore, a new technique and algorithm were developed to resolve the image scale uncertainty. This technique marks the image frames by using two laser points as independent reference points. It can also estimate and adjust image scale variations by monitoring the variations in distance between the two reference laser points. The proposed technique improves the accuracy of camera motion estimation to less than 1% error and dispenses with the necessity for camera re-calibration when the number of passengers and the load in the vehicle change. It can likewise replace the usage of sensors, such as a laser range finders or inertial measurement units, to measure the variations in camera height.

Normalized cross-correlation template matching was utilized to estimate the pixel displacement between the image frames by computing the degree of similarity between them. This method is one of the most effective methods for template matching. However, it incurs high computational cost because its underlying mechanism depends on a series of multiplication operations. Therefore, an adaptive-search template-matching technique based on vehicle

acceleration was developed to reduce the correlation computational cost, increase the allowable vehicle traveling speed and reduce the probability of template false-matching. Size of template and search area were determined and calculated to reach a trade-off between the performance and computational cost of template matching. This developed technique sped up the correlation process with more than 87% reduction in computational cost compared to the traditional full-search correlation. The factors that affect the maximum permissible vehicle driving speed were also determined and the related equations were derived. The maximum allowable vehicle speed for the developed VO is up to 6.3 m/s.

In short, the developed VO system, as well as the proposed algorithms and techniques, were successfully implemented, tested, and validated using real time kinematic GPS (RTK-GPS) with 2 cm positioning accuracy. Several indoor and outdoor experiments were conducted, and the results displayed high efficiency for the suggested techniques. Hence, the developed techniques and algorithms have high potential to be implemented in various commercial mobile robotic applications, which utilize VO for improved accuracy, efficiency, and cost effectiveness.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

SKALA TAK BERUBAH DAN PADANAN PENCONTOH SUAI-CARI UNTUK ODOMETRI VISUAL MONOKULAR DALAM PERSEKITARAN BERTEKSTUR RENDAH

Oleh

MOHAMMAD O. A. AQEL

Mei 2016

Pengerusi : Profesor Mohammad Hamiruce Marhaban, PhD
Fakulti : Kejuruteraan

Tugas yang paling penting bagi kenderaan berautonomi adalah menganggar kedudukannya dengan tepat pada setiap masa. Odometri visual adalah teknik penyetempatan yang menganggar kedudukan robot dengan hanya menggunakan aliran imej yang diperolehi dari kamera. Satu sistem odometri visual monokular menggunakan kamera tunggal menghadap ke bawah untuk menganggarkan kedudukan relatif kenderaan di persekitaran bertekstur rendah dibentangkan di dalam tesis ini. Secara umum, batasan utama sistem odometri visual sedia ada adalah berkaitan dengan kos pengiraan dan keadaan pengimejan seperti cahaya matahari, bayang-bayang, imej kabur dan variasi skala imej.

Pembuaian dalam ketinggian kamera ketika memandu di tanah yang tidak rata boleh membawa kepada perubahan dalam skala imej, yang hasilnya akan menjejaskan ketepatan anggaran kedudukan kenderaan. Oleh itu, satu teknik baru dan algoritma telah dibangunkan untuk menyelesaikan ketidaktentuan skala imej. Teknik ini bergantung kepada penandaan dua titik laser sebagai titik rujukan bebas pada imej. Variasi skala imej boleh dianggarkan dan diselaraskan dengan memantau perubahan dalam jarak antara kedua-dua titik rujukan laser. Teknik yang dicadangkan boleh meningkatkan ketepatan anggaran gerakan kamera dengan kesilapan kurang daripada 1% dan keperluan menentukur semula kamera apabila bilangan penumpang dan beban di dalam kenderaan berubah, boleh dielakkan. Teknik ini juga dapat menggantikan penggunaan peranti, seperti pencari julat laser atau unit pengukuran inersia (IMU), untuk mengukur variasi ketinggian kamera.

Walaupun kaedah korelasi silang normal adalah salah satu kaedah yang paling berkesan untuk padanan pencontoh, ia melibatkan kos pengiraan yang tinggi kerana mekanisme asasnya bergantung kepada satu siri operasi pendaraban. Oleh itu, saiz pencontoh dan kawasan pencarian terbaik telah

dipilih selepas analisis yang ekstensif dijalankan untuk mencapai keseimbangan antara prestasi dan kos pengiraan kolerasi sepadan.

Selain itu, teknik pencontoh suai-cari padanan berdasarkan pecutan kenderaan telah dibangunkan untuk meningkatkan kadar kelajuan perjalanan kenderaan yang dibenarkan dan mengurangkan kebarangkalian kesilapan-padanan pada pencontoh. Teknik yang dibangunkan juga mempercepatkan proses korelasi dengan lebih daripada 87% pengurangan kos pengiraan berbanding korelasi sepenuh carian tradisional. Faktor-faktor yang memberi kesan terhadap kelajuan maksimum kenderaan yang dibenarkan telah ditentukan dan persamaan berkaitan telah diperolehi. Kelajuan kenderaan maksimum yang dibenarkan bagi odometri visual maju adalah sehingga 6.3 m/s.

Secara ringkas, sistem odometri visual yang dibangunkan, serta algoritma dan teknik yang dicadangkan, telah berjaya dilaksanakan, diuji dan disahkan menggunakan GPS kinematik masa sebenar (RTK-GPS) dengan ketepatan kedudukan 2 cm. Beberapa eksperimen dalam dan luar telah dijalankan dan keputusan keberkesanan yang tinggi diperolehi dari teknik yang disyorkan. Oleh itu, teknik dan algoritma yang dibangunkan mempunyai potensi tinggi untuk digunakan dalam banyak aplikasi robot mudah alih komersil, yang memerlukan odometri visual tepat, cekap dan kos efektif.

ACKNOWLEDGEMENTS

Abu Huraira reported that the Prophet Mohammad (ﷺ) said,

*“**He has not thanked Allah who has not thanked people**.” [Sunan Abu Dawud 4811]*

I would like to thank, first and foremost, Almighty Allah who gave me the strength and guidance to successfully complete this PhD research. I owe my deepest gratitude to my parents for their continuous prayers, encouragement, and support. I cannot find words to express my gratitude to my beloved wife and my children for their patience throughout my PhD study.

I would like to express my deepest appreciation to my supervisory committee chair, Prof. Dr. Mohammad Hamiruce Marhaban, for his continual guidance and support with regard to my research. Without his guidance and constant assistance this successful work would not have been possible. It is with immense gratitude that I acknowledge the fatherly support and help of my committee members, Prof. Datin Dr. Napsiah Bt. Ismail and Prof. Dr. M. Iqbal Bin Saripan.

I must extend my sincere thanks to my university, Al-Azhar University-Gaza, for the opportunity it gave me to pursue my PhD study and for its support. Many thanks go to my colleagues there for their support and encouragement.
I would like to extend my thanks to Yayasan Khazanah for its continual and fatherly support of me during my PhD study. Without this support, my achievements in research would not have been possible.

Finally, sincere thanks to all of my friends for their unceasing encouragement, support and attention. I also place on record my sense of gratitude to one and all, who directly or indirectly, have lent their hand in this accomplishment. I thank all those who assisted, encouraged, and supported me during this research. May Allah bless all of you for all your contributions.

I certify that a Thesis Examination Committee has met on 13 May 2016 to conduct the final examination of Mohammad O. A. Aqel on his thesis entitled "Scale-Invariant and Adaptive-Search Template Matching for Monocular Visual Odometry in Low-Textured Environment" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

Members of the Thesis Examination Committee were as follows:

Norman bin Mariun, PhD
Professor, Ir
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Abd. Rahman bin Ramli, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Raja Mohd Kamil bin Raja Ahmad, PhD
Senior Lecturer, Ir
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Mehrdad Moallem, PhD
Professor
Faculty of Applied Sciences
Canada
(External Examiner)

ZULKARNAIN ZAINAL, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 28 June 2016

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy.

The members of the Supervisory Committee were as follows:

Mohammad Hamiruce Marhaban, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairperson)

M. Iqbal Bin Saripan, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Napsiah Bt. Ismail, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

BUJANG BIN KIM HUAT, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any other institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice Chancellor (Research and Innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software.

Signature: --- Date:--------------------------------

Name and Matric No.: Mohammad O. A. Aqel , GS35371

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under the supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

Signature:--
Name of Chairman
of Supervisory
Committee: Prof. Mohammad Hamiruce Marhaban

Signature: --
Name of Member
of Supervisory
Committee: Prof. M. Iqbal Bin Saripan

Signature: --
Name of Member
of Supervisory
Committee: Prof. Datin Napsiah Bt. Ismail

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

2D	Two Dimensional
3D	Three Dimensional
CCD	Charge-Coupled Device
DGPS	Differential Global Positioning System
FFT	Fast Fourier Transform
FOV	Field of View
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
KLT	Kanade–Lucas–Tomasi
LED	Light-Emitting Diode
LIDAR	Light Detection and Ranging Sensor
MATLAB	Matrix Laboratory
MMX	Multi-Media Extensions
NASA	National Aeronautics and Space Administration
NCC	Normalized Cross Correlation
OpenCV	Open Source Computer Vision Library
RANSAC	Random Sample Consensus
RF	Radio Frequency
RGB-D	Red-Green-Blue-Depth
ROI	Region of Interest
RTK-GPS	Real Time Kinematic- Global Positioning System

SAD	Sum of Absolute Differences
SfM	Structure from Motion
SIFT	Scale-Invariant Feature Transform
SSD	Sum of Squared Differences
SVD	Singular Value Decomposition
TOF	Time-of- Flight
UAV	Un-manned Aerial Vehicle
VO	Visual Odometry

LIST OF SYMBOLS

C	Computational cost
C_c	Principal point / Image centre C_c=[C_x,C_y]
D_{M_i}	The estimated distance between the two red points in the current image frame.
D_R	The reference distance between the two laser pointers.
f_c	Camera focal length
F_r	Camera frame rate per second
f_x	Camera horizontal focal length
f_y	Camera vertical focal length
I	Source image
$\bar{I}$	Average gray level in the source image
I_h	Image height
I_w	Image width
k	Number of shift positions for template in the search area to find the best match position
K_c	Image distortion coefficients
L_c	Distance between camera centre and vehicle's centre of rotation
Lux	Unit of illuminance and luminous emittance, measuring luminous flux per unit area which is equal to one lumen per square metre.
M_{dx}	Maximum allowable pixel displacement in the horizontal directions, which can be obtained when the template is located starting from the first pixel of the X-axis in the same direction of the motion.
M_{dy}	Maximum allowable pixel displacement in the vertical directions, which can be obtained when the template is located starting from the first pixel of the X-axis in the same direction of the motion.
M_{ext}	Camera extrinsic matrix

M_{int}	Camera intrinsic matrix
N	Number of pixels in the template image
P_h	Allowable pixel displacement per image frame when the camera image height is parallel to the direction of the longitudinal vehicle motion.
P_i	Previous position of vehicle
P_{i+1}	New position of vehicle
P_w	Allowable pixel displacement per image frame when the camera image width is parallel to the direction of the longitudinal vehicle motion.
R_c	Camera rotation matrix
R_Z	Rotation matrix *around* the Z-axis
S_i	The current scale factor of the image
S_{xs}	Horizontal shift of matching search area
S_{ys}	Vertical shift of matching search area
$(S_{ax_{i+1}}, S_{ay_{i+1}})$	The new location of the search area centre
(S_{ax_i}, S_{ay_i})	The current location of the search area centre
$(S_{ax} \times S_{ay})$	Size of the matching search area
(T_x, T_y)	Image template centre location
T	Image template
T_h	Template height
T_n	Incremental translation of vehicle in the X-axis direction
T_w	Template width
T_x	Horizontal template centre location
T_y	Vertical template centre location
T_z	Image template window size
$\overline{T}$	Average gray level in the template

T_{xs_i}	Horizontal shift required to be applied to the template location.
T_{ys_i}	The required template shift in the vertical direction.
Δu	Pixel displacements in the horizontal direction
Δv	Pixel displacements in the vertical direction
V_{h_f}	Maximum allowable vehicle driving speed in (mm/frame) when the direction of longitudinal vehicle motion is parallel to the image height.
V_{w_f}	Maximum allowable vehicle driving speed in (mm/frame) when the direction of longitudinal vehicle motion is parallel to the image width.
V_{h_s}	Vehicle speed in m/s when the direction of the longitudinal vehicle motion is parallel to the image height.
V_{w_s}	Vehicle speed in m/s when the direction of the longitudinal vehicle motion is parallel to the image width.
(X_c, Y_c, Z_c)	Camera coordinate plane
(X_v, Y_v, Z_v)	Vehicle coordinate plane
ΔX	Vehicle translation in the world coordinate plane
ΔX_c	Camera displacements in the horizontal direction
ΔY_c	Camera displacements in the vertical direction
Z_c	Height of the camera from the ground
α_c	Pixel skew coefficient
$\Delta \theta$	Vehicle orientation in the world coordinate plane
θ_y	Rotation angle around the Y-axis
θ_z	Rotation angle around the Z-axis
γ	Normalized cross correlation (NCC) coefficient

CHAPTER 1

INTRODUCTION

1.1. Background

The main prerequisite in autonomous navigation and all mobile robotic applications is an accurate localization of the robot over time. The term, "odometry" comes from two Greek words, *hodos* (meaning "journey" or "travel") and *metron* (meaning "measure") [1]; this derivation can be related to the estimate of the change in a robot's pose (translation and orientation) over time. Various types of sensors and techniques can be used for localization tasks, such as encoders, global positioning systems (GPSs), inertial navigation systems (INSs), ultrasonic or laser range finders, and visual sensors.

The encoder, also called wheel odometry, is the simplest technique available for position estimation. However, this technique suffers from position drift and inaccuracy caused by wheel slippage, which leads to an accumulation of errors over time [1, 2]. INS is an alternative technique that provides both position and orientation measurements using three-axis accelerometers and rate gyroscopes. It is also highly prone to accumulating drift; the high cost of an extremely precise INS makes it an unviable solution for commercial purposes [3]. Meanwhile, ultrasonic and laser range finders, by providing a scalar distance measurement from sensor to object, can be used for position estimation. A major drawback of these sensors, however, is the reflection of signal waves, which are highly dependent on the material or the orientation of the object surface [3].

GPS can provide an absolute position with a known ratio of error, the main advantage of which is its immunity to error accumulation over time. GPS is effective in places with a clear view of the sky but is unusable for indoor and confined spaces, as well as underground and underwater spaces [3, 4].

A highly accurate alternative sensor for estimating the ego-motion (relative motion) of robots and can avoid most of the aforementioned drawbacks is the vision sensor. Visual odometry (VO), as shown in Figure 1.1, is the localization of a robot using only the stream of images acquired from a single or multiple cameras attached to the robot [5].

Images store large and meaningful information (color, texture, shape, etc.), which are sufficient for estimating the movement of a camera in a static environment [3]. VO is an inexpensive solution that is unaffected by wheel slippage in uneven terrains. Furthermore, VO works effectively in GPS-denied environments. The rate of local drift under VO is smaller than the drift rate of wheel encoders and low-precision INSs [6]. For maximum accuracy, VO can be integrated with GPS and INS.

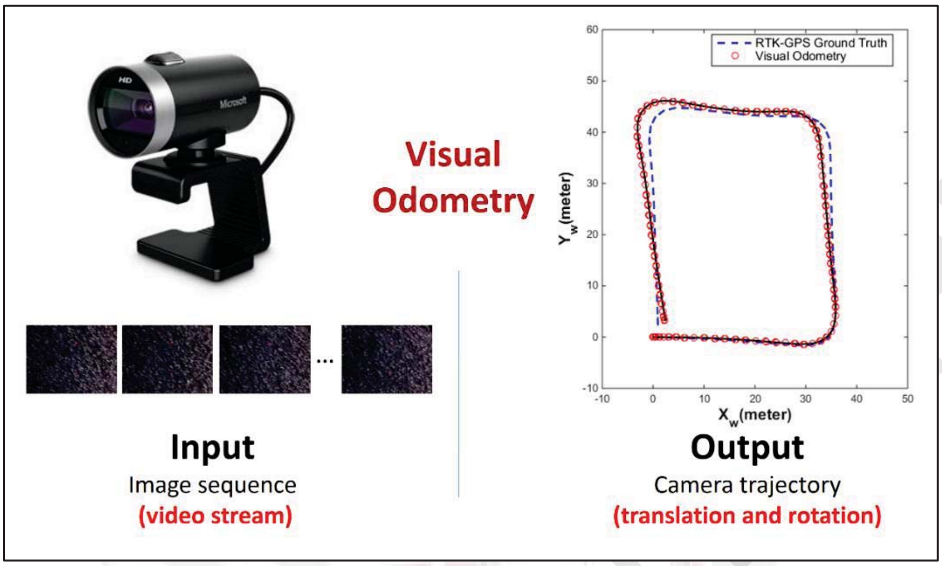

Figure 1.1: Visual odometry system

VO provides an inexpensive alternative odometry technique that is relatively more accurate than conventional techniques, such as GPS, INS, and wheel odometry. VO has a good trade-off between cost, reliability, and implementation complexity [7]. The vision-based odometry method can estimate robot location inexpensively by using a consumer-grade camera that can replace expensive sensors or systems, such as GPS and INS [2, 4, 8].

In this work, a vision-based odometry system is developed using a low-cost downward-facing monocular camera oriented toward a low-textured environment (such as an asphalt, concrete, or soil floor) to estimate the positions of ground car-like vehicles or mobile robots. Visual odometry provides an incremental online estimation of a vehicle's position by analysing the image sequences captured by a camera and integrating the pixel displacements between the image frames over time.

1.2. Problem Statement

Vision-based navigation of mobile robots is one of the main goals in computer vision and robotics research [9]. This approach is a non-contact method for the effective positioning of mobile robots, particularly in outdoor applications [10]. For autonomous navigation, the robot needs to track its own position and motion. VO provides an incremental online estimation of the vehicle position by analyzing the image sequences captured by a camera [4, 9]. The main limitations of VO systems are related to their computational cost and the light and imaging conditions (i.e., direct sunlight, shadows, image blur, and image scale variance) [10-13].

VO has been an active research area for many years [14]. However, most of the VO systems proposed in existing literature fail or cannot work effectively in outdoor environments with shadows and directional sunlight [2, 6, 11, 13, 15]. Shadow and directional sunlight have negative effects that disturb the cross-correlation matching process between image frames and lead to errors in position estimation of a vehicle.

Normalized cross-correlation is the most common method for template matching and is widely used as an effective similarity technique for matching tasks [16]. This method is highly effective for template matching because of its invariance to linear brightness and contrast variations, but it incurs high computational cost, which possibly limits response time [17]. Two parameters affect the correlation processing time: the size of the image matching search area and the size of the template window [2]. The size and location of the template window are significant in the performance of the overall system [12]. A small template window contains less information, resulting in false-matches. On the other hand, large template windows are unique but decrease allowable vehicle driving speed and increase computational cost.

Monocular vision systems suffer from scale uncertainty [18, 19]. Monocular cameras cannot estimate the change that may occur in image scales because of fluctuations in camera height from the ground [4, 8]. As discussed in [2, 4, 10, 18, 19], the image scale, which is the actual and physical size of image features, will fluctuate if the surface is uneven and the image scaling factor will be difficult to estimate. According to [18], the estimation of scaling factor may be erroneous when a large change in the road slope occurs, which may lead to an incorrect estimation of the resulting trajectory. As discussed in [2, 10], image scale variance occurs when the robot moves on non-smooth or loose soil floors that cause the wheels go up or down; thus, the distance between the camera and the ground changes, and finally, the image zooms in and out. This image scale fluctuation affects the images, making them shorter and wider than the actual scene. Such an effect prevents correct matching for visual tracking and results in poor and unreliable motion estimation. These image scale variations can disturb the calculation of pixel displacement and, finally, lead to errors in motion estimation.

The main goal of the proposed system is to ease all of the aforementioned challenges and resolve problems related to image scale uncertainty, computational cost, and non-uniform lighting and shadows.

1.3. Research Questions

i. What is the effect of image scale variations and height variations of a downward-facing camera from the ground on the accuracy of a monocular visual odometry system?

ii. Can marking the monocular image frames by two laser points with known distance between them be used as independent information to estimate the variations in image scale and camera-to-ground distance?

iii. What are the factors that can affect the total vehicle traveling speed and the quality of correlation process?

iv. What sizes for the image template and the correlation search area for template matching can best ensure a good compromise between performance and computational time?

v. How can the locations of the image template and the correlation search area be selected and changed dynamically based on a vehicle's driving acceleration in order to hasten the correlation process and increase the allowable vehicle traveling speed?

1.4. Aim and Objectives

The aim of this work is to develop a monocular VO system to estimate the relative positions of ground car-like vehicles at low-textured environments and draw their trajectories accurately. The following objectives will be addressed:

i. To develop a VO system that can estimate the relative motion of a ground car-like vehicle using a single downward-facing monocular camera and validate its performance and accuracy with respect to a real-time kinematic GPS, which is one of the most accurate ground truth positioning systems.

ii. To develop an adaptive-search correlation-based template matching technique based on vehicle traveling acceleration in order to hasten the correlation process and increase the allowable vehicle traveling speed.

iii. To propose a new estimation technique and algorithm that can estimate the variations in image scale and camera-to-ground distance and analyse the effect of these variations on the accuracy of the monocular VO.

1.5. Scope and Limitations

The scope and limitations of this research are as follows:

i. The research focuses on using a single downward-facing monocular camera to develop a VO system.

ii. The developed system estimates the relative 2D motions of ground car-like vehicles in (indoor and outdoor) low-textured environments.

iii. Owing to the lack of salient features in low-textured environments, cross-correlation template-matching technique is used in this work, rather than feature-based methods.

iv. The research is limited to an offline analysis of the image sequences captured by a camera to estimate the position of a car-like vehicle.

v. The performance of the proposed VO system is validated using a RTK-GPS ground truth system with respect to the estimation accuracy of the total vehicle travelling distance.

1.6. Research Contributions

This thesis is focused on developing an accurate monocular vision-based odometry system for ground car-like vehicles to estimate their positions in low-textured environments.

The main contributions of this work are as follows:

i. Introduction and implementation of a new approach to estimate the image scale variations and camera-to-ground distance variations in monocular VO systems.

ii. Development of an adaptive-search correlation technique to select and change the location of the correlation search area and the image template based on the vehicle traveling acceleration in order to increase the allowable vehicle traveling speed.

iii. Determining the best template size and calculate the best reduced correlation search area to reduce the correlation computational cost.

iv. Development of a data set of image streams captured by a downward-facing monocular camera attached to the vehicle to be used by researchers for future improvements.

v. Building a mathematical model that identifies and defines the factors affecting the maximum allowable vehicle driving speed in the VO system.

vi. Presenting algorithms for accurate visual-based localization along with the successful results of experiments.

1.7. Thesis Organization

The following chapters of this thesis are organized as follows.

In the next chapter, some related literature reviews are presented and discussed. The odometry and available techniques used for positioning are defined and discussed. A comparison between the VO and other alternative positioning techniques is also presented, and the approaches of VO are illustrated. After that, the details of the template-matching method used in this research are presented. Finally, the VO history and some existing related works and their challenges are discussed at the end of the chapter.

In Chapter 3, the model of the proposed system is described, and the factors affecting maximum allowable vehicle driving speed are distinguished through the equations derived from extensive analysis. Furthermore, the process for estimating the motion of a ground car-like vehicle through the calculation of image pixel displacement between consecutive image frames is explained. This chapter likewise illustrates the suggested adaptive-search correlation technique for selecting and changing both the location of the image template and the matching search area according to the vehicle's acceleration to reduce the correlation computational cost and increase the allowable vehicle traveling speed. It illustrates the proposed technique developed to estimate the image scale variations and changes in camera height from the ground.

Chapter 4 presents and discusses the results of several physical indoor and outdoor experiments conducted using the developed VO system. In addition, evaluations and validations were carried out to evaluate the accuracy of the developed technique in estimating the image scale and camera height variations in a monocular VO system, as well as evaluate the efficiency and robustness of the proposed adaptive-search correlation technique in reducing computational cost and improving the quality of correlation matching. Chapter 4 also validates the results of the developed system and compares its positioning accuracy with respect to RTK-GPS as one of the most accurate ground truth positioning systems.

Chapter 5 summarizes and concludes the research according to the results presented in this thesis. Some suggestions for further improvements in the future follow.

REFERENCES

[1] D. Fernandez and A. Price, "Visual odometry for an outdoor mobile robot," in *2004 IEEE Conference on Robotics, Automation and Mechatronics,* 2004, pp. 816-821.

[2] N. Nourani-Vatani, J. Roberts and M. V. Srinivasan, "Practical visual odometry for car-like vehicles," in *Robotics and Automation, 2009. ICRA'09. IEEE International Conference On,* 2009, pp. 3551-3557.

[3] W. Rone and P. Ben-Tzvi, "Mapping, localization and motion planning in mobile multi-robotic systems," *Robotica,* vol. 31, pp. 1-23, 2013.

[4] R. Gonzalez, F. Rodriguez, J. L. Guzman, C. Pradalier and R. Siegwart, "Combined visual odometry and visual compass for off-road mobile robots localization," *Robotica,* vol. 30, pp. 865-878, 2012.

[5] D. Scaramuzza and F. Fraundorfer, "Tutorial: Visual odometry," *IEEE Robotics and Automation Magazine,* vol. 18, pp. 80-92, 2011.

[6] A. Howard, "Real-time stereo visual odometry for autonomous ground vehicles," in *2008 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS,* 2008, pp. 3946-3952.

[7] D. Nistér, O. Naroditsky and J. Bergen, "Visual odometry," in *Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition,* 2004, pp. I652-I659.

[8] D. Nistér, O. Naroditsky and J. Bergen, "Visual odometry for ground vehicle applications," *Journal of Field Robotics,* vol. 23, pp. 3-20, 2006.

[9] J. Campbell, R. Sukthankar, I. Nourbakhsh and A. Pahwa, "A robust visual odometry and precipice detection system using consumer-grade monocular vision," in *Robotics and Automation, 2005. ICRA 2005. Proceedings of the 2005 IEEE International Conference On,* 2005, pp. 3421-3427.

[10] K. Nagatani, A. Ikeda, G. Ishigami, K. Yoshida and I. Nagai, "Development of a visual odometry system for a wheeled robot on loose soil using a telecentric camera," *Adv. Rob.,* vol. 24, pp. 1149-1167, 2010.

[11] R. Gonzalez, F. Rodriguez, J. L. Guzman, C. Pradalier and R. Siegwart, "Control of off-road mobile robots using visual odometry and slip compensation," *Adv. Rob.,* vol. 27, pp. 893-906, 2013.

[12] N. Nourani-Vatani and P. V. K. Borges, "Correlation-based visual odometry for ground vehicles," *Journal of Field Robotics,* vol. 28, pp. 742-768, 2011.

[13] Y. Yu, C. Pradalier and G. Zong, "Appearance-based monocular visual odometry for ground vehicles," in *Advanced Intelligent Mechatronics (AIM), 2011 IEEE/ASME International Conference On,* 2011, pp. 862-867.

[14] C. Wang, C. Zhao and J. Yang, "Monocular odometry in country roads based on phase-derived optical flow and 4-DOF ego-motion model," *Ind. Robot,* vol. 38, pp. 509-520, 2011.

[15] S. Lovegrove, A. J. Davison and J. Ibañez-Guzmán, "Accurate visual odometry from a rear parking camera," in *IEEE Intelligent Vehicles Symposium, Proceedings,* 2011, pp. 788-793.

[16] F. Zhao, Q. Huang and W. Gao, "Image matching by normalized cross-correlation," in *Acoustics, Speech and Signal Processing, 2006. ICASSP 2006 Proceedings. 2006 IEEE International Conference On,* 2006, pp. II-II.

[17] F. Zhao, Q. Huang and W. Gao, "Image matching by multiscale oriented corner correlation," in *Computer Vision–ACCV 2006* Anonymous Springer, 2006, pp. 928-937.

[18] B. M. Kitt, J. Rehder, A. D. Chambers, M. Schonbein, H. Lategahn and S. Singh, "Monocular visual odometry using a planar road model to solve scale ambiguity," in *Proceedings of European Conference on Mobile Robots*, 2011.

[19] A. Cumani, "Feature Localization Refinement for Improved Visual Odometry Accuracy," *International Journal of Circuits, Systems and Signal Processing,* vol. 5, pp. 151-158, 2011.

[20] J. Borenstein, H. Everett and L. Feng, "Where am I? Sensors and methods for mobile robot positioning," *University of Michigan,* vol. 119, pp. 27, 1996.

[21] J. Borenstein, H. R. Everett, L. Feng and D. Wehe, "Mobile Robot Positioning-Sensors and Techniques*," Journal of Robotic Systems,* vol. 14, pp. 231 – 249. 1997.

[22] N. Aboelmagd, T. B. Karmat and J. Georgy, "Fundamentals of Inertial Navigation, Satellite-based Positioning and their Integration," 2013.

[23] D. Wang, H. Liang, H. Zhu and S. Zhang, "A bionic camera-based polarization navigation sensor," *Sensors,* vol. 14, pp. 13006-13023, 2014.

[24] O. J. Woodman, "An introduction to inertial navigation," *University of Cambridge, Computer Laboratory, Tech.Rep.UCAMCL-TR-696,* vol. 14, pp. 15, 2007.

[25] O. Maklouf and A. Adwaib, "Performance Evaluation of GPS\ INS Main Integration Approach," *International Journal of Mechanical, Aerospace, Industrial and Mechatronics Engineering,* vol. 8, 2014.

[26] A. El-Rabbany, *Introduction to GPS: The Global Positioning System.* Artech House, 2002.

[27] G. Cook, *Mobile Robots: Navigation, Control and Remote Sensing.* John Wiley & Sons, 2011.

[28] Y. Morales and T. Tsubouchi, "DGPS, RTK-GPS and StarFire DGPS performance under tree shading environments," in *Integration*

Technology, 2007. ICIT'07. IEEE International Conference On, 2007, pp. 519-524.

[29] A. Jiménez and F. Seco, "Ultrasonic localization methods for accurate positioning," *Instituto De Automatica Industrial, Madrid,* 2005.

[30] B. Kreczmer, *Objects Localization and Differentiation using Ultrasonic Sensors.* INTECH Open Access Publisher, 2010.

[31] A. Sanchez, A. de Castro, S. Elvira, G. Glez-de-Rivera and J. Garrido, "Autonomous indoor ultrasonic positioning system based on a low-cost conditioning circuit," *Measurement,* vol. 45, pp. 276-283, 2012.

[32] J. Horn and G. Schmidt, "Continuous localization of a mobile robot based on 3D-laser-range-data, predicted sensor images, and dead-reckoning," *Robotics and Autonomous Systems,* vol. 14, pp. 99-118, 1995.

[33] T. Takahashi, *2D Localization of Outdoor Mobile Robots using 3D Laser Range Data,* Carnegie Mellon University, 2007.

[34] K. Lingemann, A. Nüchter, J. Hertzberg and H. Surmann, "High-speed laser localization for mobile robots," *Robotics and Autonomous Systems,* vol. 51, pp. 275-296, 2005.

[35] E. Frontoni, *Vision Based Mobile Robotics: Mobile Robot Localization using Vision Sensors and Active Probabilistic Approaches.* Lulu. com, 2012.

[36] K. Ni and F. Dellaert, "Stereo tracking and three-point/one-point algorithms-a robust approach in visual odometry," in *Image Processing, 2006 IEEE International Conference On,* 2006, pp. 2777-2780.

[37] R. Munguia and A. Gra, "Monocular SLAM for visual odometry," in *Intelligent Signal Processing, 2007. WISP 2007. IEEE International Symposium On,* 2007, pp. 1-6.

[38] J. Zhang, S. Singh and G. Kantor, "Robust monocular visual odometry for a ground vehicle in undulating terrain," in *Field and Service Robotics,* 2014, pp. 311-326.

[39] F. Fraundorfer and D. Scaramuzza, "Visual Odometry: Part II: Matching, Robustness, Optimization, and Applications," *Robotics & Automation Magazine, IEEE,* vol. 19, pp. 78-90, 2012.

[40] M. Maimone, Y. Cheng and L. Matthies, "Two years of visual odometry on the mars exploration rovers," *Journal of Field Robotics,* vol. 24, pp. 169-186, 2007.

[41] M. Dunbabin, J. Roberts, K. Usher, G. Winstanley and P. Corke, "A hybrid AUV design for shallow water reef navigation," in *Robotics and Automation, 2005. ICRA 2005. Proceedings of the 2005 IEEE International Conference On,* 2005, pp. 2105-2110.

[42] D. Jiang, L. Yang, D. Li, F. Gao, L. Tian and L. Li, "Development of a 3D ego-motion estimation system for an autonomous agricultural vehicle," *Biosystems Engineering,* vol. 121, pp. 150-159, 2014.

[43] E. Ericson and B. Astrand, "Visual odometry system for agricultural field robots," in *Proceedings of the World Congress on Engineering and Computer Science,* 2008.

[44] D. Valiente García, L. Fernández Rojo, A. Gil Aparicio, L. Payá Castelló and O. Reinoso García, "Visual odometry through appearance-and feature-based method with omnidirectional images," *Journal of Robotics,* vol. 2012, 2012.

[45] H. Azartash, N. Banai and T. Q. Nguyen, "An integrated stereo visual odometry for robotic navigation," *Robotics and Autonomous Systems,* vol. 62, pp. 414-421, 2014.

[46] C. Golban, S. Istvan and S. Nedevschi, "Stereo based visual odometry in difficult traffic scenes," in *Intelligent Vehicles Symposium (IV), 2012 IEEE,* 2012, pp. 736-741.

[47] H. Soltani, H. Taghirad and A. N. Ravari, "Stereo-based visual navigation of mobile robots in unknown environments," in *Electrical Engineering (ICEE), 2012 20th Iranian Conference On,* 2012, pp. 946-951.

[48] R. Siddiqui and S. Khatibi, "Robust visual odometry estimation of road vehicle from dominant surfaces for large-scale mapping," *IET Intelligent Transport Systems,* vol. 9, pp. 314-322, 2014.

[49] T. Mouats, N. Aouf, A. D. Sappa, C. Aguilera and R. Toledo, "Multispectral Stereo Odometry," *Intelligent Transportation Systems, IEEE Transactions on*, vol. 16, pp. 1210 - 1224, 2014.

[50] I. P. Alonso, D. F. Llorca, M. Gavilán, S. Á Pardo, M. Á García-Garrido, L. Vlacic and M. Á Sotelo, "Accurate global localization using visual odometry and digital maps on urban environments," *Intelligent Transportation Systems, IEEE Transactions On,* vol. 13, pp. 1535-1545, 2012.

[51] C. McManus, P. Furgale and T. D. Barfoot, "Towards lighting-invariant visual navigation: An appearance-based approach using scanning laser-rangefinders," *Robotics and Autonomous Systems,* vol. 61, pp. 836-852, 2013.

[52] Y. Jiang, Y. Xu and Y. Liu, "Performance evaluation of feature detection and matching in stereo visual odometry," *Neurocomputing,* vol. 120, pp. 380-390, 2013.

[53] R. García-García, M. A. Sotelo, I. Parra, D. Fernández, J. E. Naranjo and M. Gavilán, "3D visual odometry for road vehicles," *Journal of Intelligent and Robotic Systems,* vol. 51, pp. 113-134, 2008.

[54] G. Martinez, "Intensity-difference based monocular visual odometry for planetary rovers," in *New Development in Robot Vision* Anonymous Springer, 2015, pp. 181-198.

[55] G. Martinez, "Monocular visual odometry from frame to frame intensity differences for planetary exploration mobile robots," in *Robot Vision (WORV), 2013 IEEE Workshop On,* 2013, pp. 54-59.

[56] E. Royer, M. Lhuillier, M. Dhome and J. Lavest, "Monocular vision for mobile robot localization and autonomous navigation," *International Journal of Computer Vision,* vol. 74, pp. 237-260, 2007.

[57] Y. Jiang, G. Xiong, H. Chen and D. Lee, "Incorporating a Wheeled Vehicle Model in a New Monocular Visual Odometry Algorithm for Dynamic Outdoor Environments," *Sensors,* vol. 14, pp. 16159-16180, 2014.

[58] N. Sünderhauf and P. Protzel, "Stereo odometry—a review of approaches," *Chemnitz University of Technology Technical Report,* 2007.

[59] D. Scaramuzza and R. Siegwart, "Appearance-guided monocular omnidirectional visual odometry for outdoor ground vehicles," *Robotics, IEEE Transactions On,* vol. 24, pp. 1015-1026, 2008.

[60] R. Bunschoten and B. Krose, "Visual odometry from an omnidirectional vision system," in *Robotics and Automation, 2003. Proceedings. ICRA'03. IEEE International Conference On,* 2003, pp. 577-583.

[61] D. Scaramuzza and R. Siegwart, *Monocular Omnidirectional Visual Odometry for Outdoor Ground Vehicles.* Springer, 2008.

[62] D. Scaramuzza, F. Fraundorfer and M. Pollefeys, "Closing the loop in appearance-guided omnidirectional visual odometry by using vocabulary trees," *Robotics and Autonomous Systems,* vol. 58, pp. 820-827, 2010.

[63] J. Tardif, Y. Pavlidis and K. Daniilidis, "Monocular visual odometry in urban environments using an omnidirectional camera," in *Intelligent Robots and Systems, 2008. IROS 2008. IEEE/RSJ International Conference On,* 2008, pp. 2531-2538.

[64] J. R. Fabian and G. M. Clayton, "Adaptive visual odometry using RGB-D cameras," in *Advanced Intelligent Mechatronics (AIM), 2014 IEEE/ASME International Conference On,* 2014, pp. 1533-1538.

[65] F. Steinbrücker, J. Sturm and D. Cremers, "Real-time visual odometry from dense RGB-D images," in *Computer Vision Workshops (ICCV Workshops), 2011 IEEE International Conference On,* 2011, pp. 719-722.

[66] A. S. Huang, A. Bachrach, P. Henry, M. Krainin, D. Maturana, D. Fox and N. Roy, "Visual odometry and mapping for autonomous flight using an RGB-D camera," in *International Symposium on Robotics Research (ISRR),* 2011, pp. 1-16.

[67] Z. Fang and Y. Zhang, "Experimental Evaluation of RGB-D Visual Odometry Methods," *International Journal of Advanced Robotic Systems,* vol. 12, 2015.

[68] J. Fabian and G. M. Clayton, "Error analysis for visual odometry on indoor, wheeled mobile robots with 3-d sensors," *Mechatronics, IEEE/ASME Transactions On,* vol. 19, pp. 1896-1906, 2014.

[69] I. Dryanovski, R. G. Valenti and J. Xiao, "Fast visual odometry and mapping from RGB-D data," in *Robotics and Automation (ICRA), 2013 IEEE International Conference On,* 2013, pp. 2305-2310.

[70] C. Kerl, J. Sturm and D. Cremers, "Robust odometry estimation for RGB-D cameras," in *Robotics and Automation (ICRA), 2013 IEEE International Conference On,* 2013, pp. 3748-3754.

[71] T. Whelan, H. Johannsson, M. Kaess, J. J. Leonard and J. McDonald, "Robust real-time visual odometry for dense RGB-D mapping," in *Robotics and Automation (ICRA), 2013 IEEE International Conference On,* 2013, pp. 5724-5731.

[72] H. E. Benseddik, O. Djekoune and M. Belhocine, "SIFT and SURF Performance Evaluation for Mobile Robot-Monocular Visual Odometry," *Journal of Image and Graphics,* vol. 2, 2014.

[73] O. Naroditsky, X. S. Zhou, J. Gallier, S. Roumeliotis and K. Daniilidis, "Two efficient solutions for visual odometry using directional correspondence," *Pattern Analysis and Machine Intelligence, IEEE Transactions On,* vol. 34, pp. 818-824, 2012.

[74] C. Villanueva-Escudero, J. Villegas-Cortez, A. Zúñiga-López and C. Avilés-Cruz, "Monocular visual odometry based navigation for a differential mobile robot with android os," in *Human-Inspired Computing and its Applications*Anonymous Springer, 2014, pp. 281-292.

[75] I. Parra, M. Sotelo, D. F. Llorca and M. Ocaña, "Robust visual odometry for vehicle localization in urban environments," *Robotica,* vol. 28, pp. 441-452, 2010.

[76] D. G. Lowe, "Distinctive image features from scale-invariant keypoints," *International Journal of Computer Vision,* vol. 60, pp. 91-110, 2004.

[77] P. Kicman and J. Narkiewicz, "Concept of Integrated INS/Visual System for Autonomous Mobile Robot Operation," *Marine Navigation and Safety of Sea Transportation: Navigational Problems,* pp. 35, 2013.

[78] D. Nistér, "An efficient solution to the five-point relative pose problem," *Pattern Analysis and Machine Intelligence, IEEE Transactions On,* vol. 26, pp. 756-770, 2004.

[79] H. Stewenius, C. Engels and D. Nistér, "Recent developments on direct relative orientation," *ISPRS Journal of Photogrammetry and Remote Sensing,* vol. 60, pp. 284-294, 2006.

[80] A. E. Johnson, S. B. Goldberg, Y. Cheng and L. H. Matthies, "Robust and efficient stereo feature tracking for visual odometry," in *Robotics and Automation, 2008. ICRA 2008. IEEE International Conference On,* 2008, pp. 39-46.

[81] A. M. Zhang and L. Kleeman, "Robust appearance based visual route following for navigation in large-scale outdoor environments," *The International Journal of Robotics Research,* vol. 28, pp. 331-356, 2009.

[82] N. Bellotto, K. Burn, E. Fletcher and S. Wermter, "Appearance-based localization for mobile robots using digital zoom and visual compass," *Robotics and Autonomous Systems,* vol. 56, pp. 143-156, 2008.

[83] J. Yoo, S. S. Hwang, S. D. Kim, M. S. Ki and J. Cha, "Scale-invariant template matching using histogram of dominant gradients," *Pattern Recognit,* vol. 47, pp. 3006-3018, 2014.

[84] R. Brunelli, Ed., *Template Matching Techniques in Computer Vision: Theory and Practice.* USA: John Wiley & Sons, Ltd., 2009.

[85] M. Choi and W. Kim, "A novel two stage template matching method for rotation and illumination invariance," *Pattern Recognit,* vol. 35, pp. 119-129, 2002.

[86] A. Goshtasby, S. H. Gage and J. F. Bartholic, "A two-stage cross correlation approach to template matching," *Pattern Analysis and Machine Intelligence, IEEE Transactions On,* pp. 374-378, 1984.

[87] F. Jurie and M. Dhome, "Real time robust template matching." in *BMVC,* 2002, pp. 1-10.

[88] A. Mahmood and S. Khan, "Correlation-coefficient-based fast template matching through partial elimination," *Image Processing, IEEE Transactions On,* vol. 21, pp. 2099-2108, 2012.

[89] H. A. Kadir, M. Arshad, H. H. Aghdam and M. Zaman, "Monocular Visual Odometry for In-Pipe Inspection Robot," *Jurnal Teknologi,* vol. 74, 2015.

[90] J. Zienkiewicz and A. Davison, "Extrinsics Autocalibration for Dense Planar Visual Odometry," *Journal of Field Robotics,* 2014.

[91] L. Piyathilaka and R. Munasinghe, "An experimental study on using visual odometry for short-run self localization of field robot," in *Information and Automation for Sustainability (ICIAFs), 2010 5th International Conference On,* 2010, pp. 150-155.

[92] M. Dille, B. Grocholsky and S. Singh, "Outdoor downward-facing optical flow odometry with commodity sensors," in *Field and Service Robotics,* 2010, pp. 183-193.

[93] L. Matthies and S. Shafer, "Error modeling in stereo navigation," *Robotics and Automation, IEEE Journal Of,* vol. 3, pp. 239-248, 1987.

[94] Y. Cheng, M. Maimone and L. Matthies, "Visual odometry on the mars exploration rovers," in *Systems, Man and Cybernetics, 2005 IEEE International Conference On,* 2005, pp. 903-910.

[95] L. Li, J. Lian, L. Guo and R. Wang, "Visual Odometry for Planetary Exploration Rovers in Sandy Terrains," *Int J Adv Robotic Sy,* vol. 10, 2013.

[96] D. M. Helmick, Y. Cheng, D. S. Clouse, L. H. Matthies and S. Roumeliotis, "Path following using visual odometry for a mars rover in high-slip environments," in *Aerospace Conference, 2004. Proceedings. 2004 IEEE,* 2004, pp. 772-789.

[97] D. Van Hamme, W. Goeman, P. Veelaert and W. Philips, "Robust monocular visual odometry for road vehicles using uncertain perspective projection," *EURASIP Journal on Image and Video Processing,* vol. 2015, pp. 1-21, 2015.

[98] B. Lee, K. Daniilidis and D. D. Lee, "Online self-supervised monocular visual odometry for ground vehicles," in *Robotics and Automation (ICRA), 2015 IEEE International Conference On,* 2015, pp. 5232-5238.

[99] C. Forster, M. Pizzoli and D. Scaramuzza, "SVO: Fast semi-direct monocular visual odometry," in *Robotics and Automation (ICRA), 2014 IEEE International Conference On,* 2014, pp. 15-22.

[100] P. Corke, D. Strelow and S. Singh, "Omnidirectional visual odometry for a planetary rover," in *Intelligent Robots and Systems, 2004. (IROS 2004). Proceedings. 2004 IEEE/RSJ International Conference On,* 2004, pp. 4007-4012.

[101] S. Choi, J. Park and W. Yu, "Simplified epipolar geometry for real-time monocular visual odometry on roads," *International Journal of Control, Automation and Systems,* vol. 13, pp. 1454-1464, 2015.

[102] R. Hartley and A. Zisserman, *Multiple View Geometry in Computer Vision.* Cambridge university press, 2004.

[103] D. Scaramuzza, F. Fraundorfer, M. Pollefeys and R. Siegwart, "Absolute scale in structure from motion from a single vehicle mounted camera by exploiting nonholonomic constraints," in *Computer Vision, 2009 IEEE 12th International Conference On,* 2009, pp. 1413-1419.

[104] S. Guo and C. Meng, "Monocular visual odometry and obstacle detection system based on ground constraints," in *Social Robotics* Anonymous Springer, 2012, pp. 516-525.

[105] J. Bouguet. (2nd December, 2013). *Camera Calibration Toolbox for Matlab*. Available: http://www.vision.caltech.edu/bouguetj/calib_doc/index.html.

[106] (21st November 2012). *What is OpenCV? OpenCV vs. MATLAB- An insight*. Available: https://karanjthakkar.wordpress.com/2012/11/21/what-is-opencv-opencv-vs-matlab/.