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**UNIVERSIDADE ESTADUAL PAULISTA**
CAMPUS DE PRESIDENTE PRUDENTE
**FACULDADE DE CIÊNCIAS E TECNOLOGIA**
*Programa de Pós-Graduação em Ciências Cartográficas*

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# A PORTABLE MOBILE TERRESTRIAL SYSTEM WITH OMNIDIRECTIONAL CAMERA FOR CLOSE RANGE APPLICATIONS

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Thesis presented to "*Programa de Pós Graduação em Ciências Cartográficas*" at São Paulo State University – UNESP - School of Technology and Sciences.
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TÍTULO DA TESE: A PORTABLE MOBILE TERRESTRIAL SYSTEM WITH OMNIDIRECTIONAL CAMERA FOR CLOSE RANGE APPLICATIONS

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# ABSTRACT

This research proposes a new technique for close-range mobile data acquisition and processing, consisting of a backpacked light-weight low-cost system. This system integrates an omnidirectional camera and a GPS/IMU system (Global Positioning Systems/Inertial Measurement Unit System) with a tailored photogrammetric processing chain to obtain sensor location and 3D points coordinates using the fisheye images. Omnidirectional systems, based on multiple cameras covering a full-spherical field of view, have been used in close range photogrammetry applications. The use of omnidirectional systems is especially motivated by their 360° coverage around the sensor, which allows more features to be tracked in a single image shot, and by the light weight and low cost of some off-the-shelf omnidirectional cameras. This kind of systems have been named as Personal Mobile Terrestrial System (PMTS). There are only few studies focusing on PMTS using omnidirectional systems. This research assessed the performance of an omnidirectional PMTS based exclusively on low-cost technologies to indirectly estimate forest and outdoor urban features. An accuracy evaluation of GPS and IMU sensors and the development of rigorous photogrammetric processing considering fisheye geometry were performed. PMTS data, i.e fisheye images and navigation data, are input information for the photogrammetric process. The proposed photogrammetric process focused on omnidirectional camera modelling, feature-based matching and bundle adjustment considering fisheye geometry. Experimental assessments showed that the integrated sensor orientation approach using navigation data as the initial information and a rigorous photogrammetric process can increase the trajectory accuracy, especially in obstructed areas, such as dense tropical forests and some urban environments. Overall, using a postprocessing approach with PMTS data and ground control points, the EOPs (Exterior Orientation Parameters) were estimated with standard deviations of 0.1° for sensor attitude and centimetric accuracy for sensor position. The point cloud generated had an accuracy consistent with the range of the pixel size in the object space units in the central part of omnidirectional images (3.5–8 cm). A PMTS real-time application was simulated in laboratory. The PMTS trajectory was estimated with a planialtimetric accuracy of 0.7 m, while, the 3D map was simultaneously computed with an average accuracy ranging between 0.5 m and 2 m.



**Keywords:** Personal mobile terrestrial system, Mobile mapping, Polydioptric system calibration, Omnidirectional image matching, Incremental bundle adjustment.

## CONTENTS

# CHAPTER I
# INTRODUCTION



# CHAPTER II
# A PERSONAL MOBILE TERRESTRIAL SYSTEM: DEVELOPMENT AND APPLICATIONS



# CHAPTER III
# GEOMETRIC MODEL OF A DUAL-FISHEYE 360° IMAGING SYSTEM

## CHAPTER IV
## A RECURSIVE FEATURE SEARCH METHOD FOR FISHEYE IMAGE MATCHING



## CHAPTER V
## AN INCREMENTAL BUNDLE ADJUSTMENT BASED ON WIDE ANGLE IMAGE GEOMETRY

## CHAPTER VI
## FINAL REMARKS

# CHAPTER I
# INTRODUCTION

## 1. OVERVIEW AND MOTIVATION

Mobile Mapping Technologies have begun to be developed and earn attention in the last few years. They can provide fast, cost-effective and complete data collection, considering the dynamic and continuous displacement of the sensors. Mobile Terrestrial Systems (MTS) are composed of navigation and remote sensors, such as cameras and LASER scanners, integrated in a common moving platform (SCHUWARZ and EL-SHEIMY, 2004). Different types of platforms can be used in terrestrial mapping, such as cars (KUKKO et al., 2012), small Unmanned Aerial Vehicles (SHEN et al., 2012, ROCA et al., 2013), boats (MORAES et al., 2016), ground robots (KLINGENSMITH et al., 2016), and a person as operator (KUKKO et al., 2012; CORSO and ZAKHOR, 2013; LIANG et al., 2014; WEN et al., 2016; FORSMAN et al., 2016 and OVELAND et al., 2017). Therefore, the motivation of this Ph.D. research is driven on how to acquire indirect data with a ground perspective in difficult access places, such as forest and urban environments, considering an accurate, economic and fast methodology.

Personal Mobile Terrestrial System (PMTS) consists of a set of sensors that are carried by a human operator, for instance in a backpack, to acquire measurements of the environment while walking. The use of PMTS is increasing in mobile mapping applications, because they are offering dynamic data acquisition on ground perspective in places where the use of wheeled platforms is unfeasible, such as forest and some city mapping application (sidewalks and indoor buildings). PMTS have become more popular with emerging technologies, for instance, miniaturized navigation sensors and off-the-shelf omnidirectional cameras, enabling flexible and low-cost mobile mapping approaches.

Emerging sensor technologies are changing the way of mapping the environment. Sensors with nonconventional internal geometry, i.e., omnidirectional, have been increasingly used in Close Range Photogrammetry (CRP) applications. However, most of these sensors have not been developed for high accuracy metric purposes, and therefore rigorous methods are required in data acquisition and processing chain to obtain satisfactory results. Thus, in order to contribute to the development of a lite PMTS and potential applications of these off-the-shelf sensors, this research presents a low-cost PMTS approach composed by an omnidirectional camera with two fisheye lenses and off-the-shelf inertial navigation system, specially arranged in a backpack, aiming close-range applications. Our study was the first to assess the performance of a low-cost backpack-mounted system with omnidirectional camera in the estimation of forest and urban parameters, focusing on the accuracy evaluation of low-cost GPS (Global Positioning Systems) receiver and MEMS-IMU (Microelectromechanical systems - Inertial Measurement Unit) sensors and on the development of photogrammetric processing methodologies using an omnidirectional system.

Omnidirectional systems, based on multiple cameras that cover a full-spherical field of view, are an attractive alternative due to the imaging of larger areas, which allows more features to be tracked in a single image, and the low-weight and low-cost of these cameras that have recently entered the market (e.g. Giroptic 360cam, Go Pro 360°, Kodak PixPro SP360, Google Jump system, Ricoh Theta S, Samsung Gear 360 and LG 360). Therefore, the proposed PMTS will enable a dynamic image acquisition of a set of features, simultaneously, in different perspectives, for a fast and systematic terrestrial surveying. However, the usability of omnidirectional sensors requires adaptations in the classic photogrammetric process, considering its sensor geometry particularities. The challenges of fisheye images include nonperspective inner geometry, huge scale and illumination variations between scenes, large radial distortion and nonuniformity of spatial resolution. In this regard, this research aims to extend the well-known photogrammetric process from the perspective to omnidirectional images improving PMTS results, which involves omnidirectional system modelling, fisheye image matching and a sequential bundle adjustment using fisheye images. PMTS developments and data processing are the main subjects assessed and discussed in the following sections.

## 1.1 OBJECTIVES

The main goal of this research is to develop a methodology for close-range data acquisition with a portable mobile terrestrial system and a photogrammetric processing chain to obtain 3D points coordinates with fisheye images. In this regard, the Ph.D. research has the following specific objectives:

(1) To evaluate the feasibility of a low-cost PMTS with omnidirectional system for forest and city mapping;

(2) To model the Ricoh Theta S omnidirectional system inner geometry, studying a suitable method for the calibration of a Poly-dioptric spherical imaging systems, based on fisheye lenses models;

(3) To investigate the performance of state-of-art interest operators for omnidirectional image, identifying the main limitations and proposing improvements on Feature-Based Matching (FBM) techniques for original fisheye images;

(4) To study mathematical models and stochastic treatment of image observations obtained with omnidirectional cameras based on fisheye lenses to be applied in an incremental bundle adjustment with the PMTS data, aiming the estimation of Exterior Orientation Parameter (EOP) and a 3D sparse point cloud in real-time applications.

## 1.2 CONTENT AND CONTRIBUTIONS

Thesis content can be summarized in two main purposes: PMTS development and feasibility study (Chapter 2) and photogrammetric processes (Chapter 3 to Chapter 5) considering fisheye image geometry (omnidirectional system calibration, fisheye image matching and incremental bundle adjustment). Chapter 2 summarizes the studies developed by Campos et al. (2017), Campos et al. (2018a) and Castanheiro et al. (2018). A new PMTS approach with a low-cost backpack-mounted omnidirectional camera system is introduced. A technical description of the proposed PMTS, which includes sensors setup, integration and synchronization, is presented. Then, a PMTS feasibility study for forest and outdoor city mapping applications is performed. The results obtained are compared with other PMTS approaches.

Chapter 3 is based on the work presented by Campos et al. (2018b), and, it presents a process for the calibration of a poly-dioptric spherical imaging systems (for instance, Ricoh Theta S), in order to enable their metric use in close-range photogrammetry applications. The calibration methodology proposed is based on fisheye lenses models. Experiments were performed to verify the set of interior and relative orientation parameters that better reproduces the bundle that generated the 360° image of Ricoh Theta S. The main contribution presented in this chapter is a simultaneous bundle adjustment approach with stability constraints on base elements and rotation matrix angles, which achieved accuracies comparable with conventional photogrammetric calibration with perspective cameras.

Chapter 4 presents an approach to improve FBM techniques on fisheye images with a recursive reduction of the search space based on epipolar geometry. The epipolar restriction is computed with the equidistant mathematical model and initial EOPs determined from the PMTS navigation sensors. The interest points are detected with the SIFT (Scale-Invariant Feature Transform) operator and the candidate matches are searched in a reduced search space. Experimental assessments were performed with data sets collected by the proposed PMTS, aiming outdoor applications. This chapter extends the study presented by Castanheiro et al. (2017).

Chapter 5 proposes an incremental bundle adjustment to estimate omnidirectional sensor position and attitude (sensor pose) and the 3D tie points coordinates (map points) simultaneously during PMTS acquisition. A methodology for PMTS data acquisition and processing based on Chapters 2 to 4 are applied. A mathematical model consistent with the omnidirectional sensor geometry and a stochastics modeling of the PMTS data are assessed. The summary of thesis results and conclusions are presented in Chapter 6.

## 1.3 INTERNATIONAL COOPERATION

This Ph.D. research is linked to an international project jointly conducted by researchers from São Paulo State University (UNESP) and the Finnish Geospatial Research Institute in the National Land Survey of Finland (FGI) funded by FAPESP (Fundação de Amparo a Pesquisa do Estado de São Paulo - Grant: 2013/50426-4) and AKA (Academy of Finland - Grant: 273806). The project “Unmanned Airborne Vehicle - based 4D Remote Sensing for Mapping Rain Forest Biodiversity and Its Change in Brazil (UAV_4D_Bio)” aims to develop methodologies and technologies for biodiversity mapping and for indicators of environmental change in Evo test forest in Finland and in regeneration areas of tropical forest in the interior of São Paulo State.

# CHAPTER VI
# FINAL REMARKS

In this work a PMTS with omnidirectional system for forest and urban mapping was proposed. A performance assessment of this system focusing in the photogrammetric process using fisheye images was presented. This final chapter discuss the open problems for future works based on the achieved results. The PMTS provided centimetric accuracy for object reconstruction and trajectory estimation in a postprocessing approach (Chapter 2). In a real-time application, a meter level accuracy for object reconstruction and a trajectory accuracy of 0.66 m was obtained. Therefore, passive optical systems can be considered a feasible alternative in covered areas, where GPS signal is not often available. However, system features (Chapter 2) can be improved (remarks 1 to 3).

(1) Some concerns about the imaging system used (Ricoh Theta S) remains. The 8s time gap between successive still images with the Ricoh Theta S prevents the dynamic sequential acquisition of images, leading to the decision of using frame videos with lower resolution in our system, which impaired the imaging range of the PMTS. Other dual systems can be assessed to improve the proposed PMTS and the data acquisition procedure. Furthermore, in the study of the Ricoh Theta S inner geometry (Chapter 3), it was noticed that the field of view of each camera covers more than 180° (the same targets appear in images of both sensors), which was not well-modeled by the proposed mathematical model. A suitable treatment of this geometry is required.

(2) Remarking the navigation system used (Chapter 2), MEMS measurement still provides high level of errors and noise. The MEMS-sensors uncertainty must be considered in the stochastic model. Especially aiming real-time application, these errors can result in a quick drift of the solution. Higher quality navigation systems should be assessed in future improvements of this system.

(3) The proposed PMTS was assessed mainly in outdoor environments. Therefore, the data acquisition methodology can be evaluated for other datasets and the PMTS can be modified, aiming for instance, indoor or agriculture applications. Other sensors, such as TLS, can be incorporated to the PMTS platform, resulting in many possibilities of multi-sensor systems and data processing methodologies.

The classical photogrammetric processes were extended from the perspective to omnidirectional case to improve PMTS results (Chapter 3 to 5). A recursive feature search method for fisheye image matching ($SIFT_{RFS}$) was presented in Chapter 4. Chapter 5 presented a methodology for incremental bundle adjustment to evaluate the potential of the proposed PMTS in real time CRP applications. Many improvements are still required to automate the PMTS process for robust real-time applications. The main challenge is to reach a strong network of matches to the incremental bundle adjustment, using automatic image points measurements considering fisheye image geometry, which open many research opportunities, as following (remarks 4 to 8).

(4) FBM techniques, such as SIFT, provided a minimum number of conjugate points detected in a sequential pair of fisheye images (defined in this work as repeatability). The low repeatability can be explained by the significant and quick appearance change of the features in function of the PMTS displacement using fisheye images, affecting key point stability and match comparison. The appearance changes can be mitigated with a local rectification, as initially proposed by Daniilidis (2002). For instance, fisheye image templates can be projected from the sphere surface to a vertical plane, considering different distances of projection. These templates can be defined using the proposed epipolar line technique.

(5) The evaluation of the consistency of the geometry of the keyframes to support a robust point network configuration is required. In our work, a range of fisheye images was defined according to the baseline and a minimum number of matches to avoid exhaustive matching. However, the detection and exclusion of poor or degenerated camera configurations was not performed. Usually in the perspective case, a poor camera configuration results from a small ratio between the baseline length and the depth of the scene, as discussed by Michelini and Mayer (2014). The challenge for fisheye images comes with the huge depth and scale variation. For instance, a keyframe with optimal Base/Depth ratio can provide a low number of matches, and thus, a criterion to analyze the geometric consistent of keyframes needs to consider the specific fisheye features. An approach considering graph-based optimization is suggested.

(6) The presence of outliers and the weak geometry of match points are point out in related works as the main reasons for the drift of the bundle adjustment solution (SCARAMMUZZA et al., 2009). Automatic outlier detection is a complex task in omnidirectional systems. Different sources of error can be mentioned from the image matching process. The number of false matches detected using FBM techniques is larger in fisheye images than those

usually achieved on standard perspective images, due to the huge variations both in illumination and appearance. Furthermore, points with weak geometry, poor intersection of rays or in the infinity, i.e. clouds (especially in outdoor applications), need to be identified. In our work, the outliers were manually detected based on the image coordinate residuals in the x and y directions from a previously postprocessing bundle adjustment. Therefore, the dataset used in Chapter 5 can be considered optimal and further experiments considering an automatic selection of inliers and outliers for the bundle adjustment is recommended.

(7) The proposed methodology for the photogrammetric process focused in the fisheye lens geometry. The mathematical model used in the camera calibration process and in the incremental bundle adjustment was based on the equidistant projection. Considering the experiments performed with the most popular fisheye lenses models, the equidistant equation best fits for Ricoh Theta S. However, this mathematical model (equidistant) does not describe the geometry of all observations, since some image compressions were noticed (Chapter 5), requiring further investigations. The methodology proposed can be extended to other omnidirectional sensors considering other fisheye lens equations. Furthermore, mathematical models based in the collinearity condition in the sphere domain (Equation 36) and general mathematical model as proposed by Kannala and Brandt (2006) and Urban et al. (2017) should also be assessed.

(8) The reliability of the 3D reconstruction of the environment depends on the quality of the data acquired, which are affected by different sources of errors. Therefore, real time assessment of data quality and error prediction, especially regarding autonomous systems, are necessary to help users to understand the level of uncertainty during the data acquisition and intervene, whenever necessary. In future works an expected PMTS outcome can inform the user about the quality throughout the whole data collection.

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