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LETÍCIA FERRARI CASTANHEIRO

GEOMETRIC MODEL OF A DUAL-FISHEYE SYSTEM COMPOSED OF HYPER-HEMISPHERICAL LENSES

Presidente Prudente - SP
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GEOMETRIC MODEL OF A DUAL-FISHEYE SYSTEM COMPOSED OF HYPER-HEMISPHERICAL LENSES

Master's thesis presented to "Programa de Pós-Graduação em Ciências Cartográficas" at School of Sciences and Technology of São Paulo State University – FCT/UNESP to obtain the degree of master of Cartographic Sciences.

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“We must have perseverance and above all confidence in ourselves.”

Marie Curie

“You only learn from experience, so as much as someone can tell you things, you have to go out there and make your own mistakes in order to learn.”

Emma Watson

RESUMO

A combinação de duas lentes com FOV hiper-hemisférico em posição opostas pode gerar um sistema omnidirecional (FOV 360°) leve, compacto e de baixo custo, como Ricoh Theta S e GoPro Fusion. Entretanto, apenas algumas técnicas e modelos matemáticos para a calibração um sistema com duas lentes hiper-hemisféricas são apresentadas na literatura. Nesta pesquisa, é avaliado e definido um modelo geométrico para calibração de sistemas omnidirecionais compostos por duas lentes hiper-hemisféricas e apresenta-se algumas aplicações com esse tipo de sistema. A calibração das câmaras foi realizada no programa CMC (calibração de múltiplas câmeras) utilizando imagens obtidas a partir de vídeos feitos com a câmara Ricoh Theta S no campo de calibração 360°. A câmara Ricoh Theta S é composto por duas lentes hiper-hemisféricas *fisheye* que cobrem 190° cada uma. Com o objetivo de avaliar as melhorias na utilização de pontos em comum entre as imagens, dois conjuntos de dados de pontos foram considerados: (1) apenas pontos no campo hemisférico, e (2) pontos em todo o campo de imagem (isto é, adicionar pontos no campo de imagem hiper-hemisférica). Primeiramente, os modelos ângulo equisólido, equidistante, estereográfico e ortogonal combinados com o modelo de distorção Conrady-Brown foram testados para a calibração de um sensor da câmara Ricoh Theta S. Os modelos de ângulo-equisólido e estereográfico apresentaram resultados melhores do que os outros modelos. Portanto, esses dois modelos de projeção foram utilizados em uma calibração simultânea da câmera (ou seja, ambos os sensores Ricoh Theta S foram considerados em um mesmo procedimento). POIs (parâmetros de orientação interior) e POEs (parâmetros de orientação exterior) de ambos os sensores, e POR (parâmetros de orientação relativa) foram estimados em um ajustamento de blocos com injunção de estabilidade dos ROPs. Os modelos ângulo-equisólido e estereográfico apresentaram bons resultados com o uso dos pontos na área hiper-hemisférica da imagem para a estimação dos POIs, POEs e PORs. No entanto, o ajustamento baseado no modelo ângulo-equisólido com injunção de estabilidade apresentou os melhores resultados. Neste trabalho, também é apresentado duas aplicações com sistemas omnidirecionais: mapeamento 3D de uma área urbana usando um sistema de mapeamento móvel terrestre, composto pela câmara Ricoh Theta S, e a geração da nuvem 3D de uma área agrícola com a câmara GoPro Fusion, que também é composta por duas lentes hiper-hemisféricas. Ambos experimentos apresentaram o potencial do uso de sistemas omnidirecionais na geração de nuvem de pontos fotogramétrica e extração de atributos importantes para cada aplicação.

Palavras-chaves: lente hiper-hemisférica; modelos de projeção *fisheye*; sistema omnidirecional; sistema polidióptrico; calibração de múltiplas câmaras; injunção de estabilidade; mapeamento 3D.

ABSTRACT

The arrangement of two hyper-hemispherical fisheye lenses in opposite position can design a light weight, small and low-cost omnidirectional system (360° FOV), e.g. Ricoh Theta S and GoPro Fusion. However, only a few techniques are presented in the literature to calibrate a dual-fisheye system. In this research, a geometric model for dual-fisheye system calibration was evaluated, and some applications with this type of system are presented. The calibrating bundle adjustment was performed in CMC (calibration of multiple cameras) software by using the Ricoh Theta video frames of the 360° calibration field. The Ricoh Theta S system is composed of two hyper-hemispherical fisheye lenses with 190° FOV each one. In order to evaluate the improvement in applying points in the hyper-hemispherical image field, two data set of points were considered: (1) observations that are only in the hemispherical field, and (2) points in all image field, i.e. adding points in the hyper-hemispherical image field. First, one sensor of the Ricoh Theta S system was calibrated in a bundle adjustment based on the equidistant, equisolid-angle, stereographic and orthogonal models combined with Conrady-Brown distortion model. Results showed that the equisolid-angle and stereographic models can provide better solutions than those of the others projection models. Therefore, these two projection models were implemented in a simultaneous camera calibration, in which the both Ricoh Theta sensors were considered in a same procedure. IOPs (interior orientation parameters) and EOPs (exterior orientation parameters) of both sensors, and a set of ROPs (relative orientation parameters) were estimated in a bundle adjustment based on stability constraints of ROPs. Both equisolid-angle and stereographic models presented good performances; meanwhile, the equisolid-angle model showed more stable results than stereographic model when adding observation in the hyper-hemispherical image field. In this research, two applications applying dual-fisheye cameras are also investigated: 3D city mapping using a PMTS (portable mobile terrestrial system) that is composed of Ricoh Theta S dual-camera, and 3D crop modelling using GoPro Fusion dual-camera. Both experimental assessments presented the potential advantage of using the omnidirectional system to generate a 3D point cloud, in which can extract important attributes for each application.

Keywords: hyper-hemispherical lens, fisheye projection model, omnidirectional system, polydioptric system, multi-camera calibration, stability constraints, 3D mapping.

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CHAPTER I
INTRODUCTION

1 OVERVIEW AND MOTIVATION

The design of high performance imaging systems to cover a full-spherical field of view (FOV) is a trend in the applied optical research. Multiple cameras arranged in the same structure, which enables a 360° FOV panorama, have been used for virtual reality, surveillance, robotic navigation and driverless vehicle applications. The overlap between images from each camera that composes the multi-camera system is an important issue to create panoramic images without blind zones. This is a current topic in recent works for multi-camera design (Fangi et al., 2013; Pernechele et al., 2018, Song et al., 2018, Ye et al., 2018, Lian et al., 2018). Furthermore, common points between sensor images can improve the system calibration, since the bundles of rays that formed the 360° image are considered.

A multi-camera system can be designed with perspectives lenses, which have a limited FOV, consequently, many cameras are needed to cover a full-spherical panorama. An example of omnidirectional system with perspectives cameras is Ladybug 5, which is composed of six cameras with 89.3° FOV (Khoramshahi et al., 2019). Another design option is to use fisheye lenses, in which fewer lenses are required to cover a large panorama due to the large FOV. The disadvantage is the loss of resolution caused by projection compression, mainly in the limits of the image. However, some authors have highlighted the benefits of using lenses with large FOV like fisheye lenses (Zhang et al., 2016; and Matsuki et al., 2018). For instance, a larger spatial distribution of points and a bigger overlap between sequence images can be tracked by fisheye lens cameras due to the large FOV.

Fisheye lenses can be classified as hemispherical (110° - 180° FOV) or hyper-hemispherical (FOV above 180°). Nowadays, the use of lenses with FOV wider than 180° has been a trend in omnidirectional systems. Just two hyper-hemispherical lenses in back-to-back position can provide lightweight and low-cost full-spherical systems (e.g., Ricoh Theta S), while maintaining the overlap between sensor images. This compact design has motivated the use of dual-fisheye system in personal mobile terrestrial system for 360° imaging, as presented by Campos et al. (2018b). Furthermore, the complexity of camera calibration is reduced for dual-fisheye system, since only two sets of IOPs (interior orientation parameters) and EOPs (exterior orientation parameters), and a set of ROPs (relative orientation parameters) have to be estimated. Reducing the number of camera to be triggered simultaneously also facilitate their synchronization.

Considering the high potential of 360° imaging for photogrammetric measurements (Campos et al., 2018b; Castanheiro et al., 2018; Castanheiro et al., 2020), some studies have focused on camera calibration (Aghayari et al., 2017; Campos et al., 2018a) and photogrammetric applications (Caruso et al., 2015; Meegoda et al., 2018; Perfetti et al., 2018; Campos et al., 2019; Tommaselli et al., 2019) of these multi-camera systems based on fisheye lenses. However, only few studies proposed mathematical models that consider the image observation geometry over 180° FOV for photogrammetric applications. Thus, these points are usually excluded from the photogrammetric procedure, such as camera calibration and image orientation. For instance, Campos et al. (2018a) presented a methodology to calibrate a multi-camera system composed of two hyper-hemispherical fisheye cameras based on the equidistant mathematical model. In this work, the points in the hyper-hemispherical image field were removed from the camera calibration procedure because of the double mapping problem, which occurs due to the arctan function in the equidistant model. This problem was circumvented by Van den Heuvel et al. (2006) and Song et al. (2018) using a generic polynomial model to calibrate a hyper-hemispherical fisheye lens. Other models have been proposed in literature for hyper-hemispherical lens modelling (Khomutenko et al., 2016; Pernechele, 2016). However, fisheye projections models were not yet sufficiently explored for photogrammetric procedures with hyper-hemispherical lenses in the literature.

Besides a suitable mathematical model, an accurate multi-camera system calibration also depends on a suitable technique to estimate IOPs, EOPs and ROPs. Many researches have proposed a bundle adjustment with constraints on relative image orientation (He et al., 1993; Lerma et al., 2010; Habib et al., 2014; Detchev et al., 2018). Some studies have presented improvements in the multi-camera system calibration when using ROPs as stability constraints (Tommaselli et al., 2013; Lichti et al., 2015; Campos et al., 2018a; Jarron et al., 2019). This technique is based on the stability of the cameras during image acquisition. Nowadays, multi-camera systems have been constructed with cameras in a same structure, known as polydioptric system (Maas, 2008). This arrangement can design a more stable omnidirectional system. Therefore, the concept of stability constraints can be used as proposed by Tommaselli et al. (2009; 2013). Meanwhile, the use of relative orientation stability constraints, for dual-fisheye system, has been rarely approached in the literature.

This research presents a study on fisheye mathematical models based on equidistant, equisolid-angle, stereographic, and orthogonal projections combined with the Conrady-Brown distortion model. These models were tested in a camera calibration by bundle adjustment with the Ricoh Theta system to evaluate the contribution of using points in the hyper-hemispherical image field. The four fisheye models were assessed for the Ricoh Theta sensor using images taken in the 360° calibration field and CMC (calibration of multiple camera) software. The models that achieved the best results were implemented in the CMC software to calibrate both Ricoh Theta sensors in a simultaneous bundle adjustment based on stability constraints of relative rotation matrix and base element. A further analysis was performed for ROP estimation with and without using stability constraints. In this research, two experimental assessments with two different dual-fisheye systems in close-range applications were also performed: 3D city mapping using a PMTS (portable mobile terrestrial system), composed of Ricoh Theta S dual-camera; and 3D crop modelling using GoPro Fusion dual-camera. Both experimental assessments presented the potential of using an omnidirectional system to generate 3D point clouds, in which important attributes can be extracted depending on the application.

CHAPTER VI
CONCLUSION AND RECOMENDATIONS

6 CONCLUSION

A mobile system with a dual-fisheye camera can be a feasible option. A larger spatial distribution of points can be obtained using a camera with larger FOV, mainly for environments with sparse features, such as indoor environments (Caruso et al., 2015; Matsuki et al., 2018). Another advantage is the larger overlap between sequential images; therefore, an object point is observed in a long period of image acquisition (Matsuki et al., 2018). The benefits on using large FOV images were presented in details by Zhang et al. (2016) and Matsuki et a. (2018). In this regards, fisheye models have been implemented in scientific and commercial software due to the growing use of fisheye images for accurate applications, which can be considered a trend in close range photogrammetry. However, some limitations when using a dual-fisheye camera can be highlighted.

Generally, dual-fisheye systems are composed of two hyper-hemispherical fisheye lenses to maintain the overlap between sensor images. Most of fisheye lenses follow the equidistant projection (Abraham and Frostner, 2005), as the Agisoft Photoscan/Metashape that uses the equidistant fisheye model. However, the equidistant model, as well orthogonal model, do not correctly model observations beyond 180°, being required to remove them to achieve accurate results (Campos et al., 2018a; Castanheiro et al., 2020). These common points between images from both sensors can improve some photogrammetric techniques, such as camera calibration. Therefore, further fisheye models were assessed with camera calibration bundle adjustment of one Ricoh Theta sensor. The equisolid-angle and stereographic models presented the best results. The a-posteriori values were 0.34 and 0.63 respectively, with a unit a-priori value, and both models achieved a RMSE of discrepancies between control and estimated distance of 6 mm. The affinity parameters were removed from the calibration procedures, since the effects in the image coordinates were less than 0.5 pixels.

Regarding the calibration of both Ricoh Theta sensors in the same process (simultaneous calibration with bundle adjustment), improvements were noticed in the estimated standard deviations of EOPs and IOPs when using points in the hyper-hemispherical image field, which were covered by both sensors. Furthermore, the use of ROPs as stability constraints improved the ROPs estimation. The best results for the calibration Ricoh Theta S dual-camera were achieved by equisolid-angle model combined with Conrady-Brown's distortion model, considering the relative rotation elements and base components as stability constraints.

Two different dual-fisheye cameras (Ricoh Theta S and GoPro Fusion) were assessed for 3D modelling an urban area and an agricultural crop. Both experimental assessments presented that omnidirectional system composed of dual-fisheye camera can be a feasibility choice for 3D mapping. Considering the uncertainties in the process of generating 360° equirectangular images from Ricoh Theta S, the video frames are more suitable for applications that require high accuracy, such as close-range photogrammetry, because the original geometry is preserved. A disadvantage of fisheye video frames is the low resolution of the frames compared to the still image. Other omnidirectional system can be considered suitable to use in a portable mobile mapping, for instance, GoPro Fusion preserves the original fisheye images from each sensor without any processing, which is suitable for a rigorous photogrammetric chain.

Some recommendations for future works can be mentioned: (1) the calibration approach tested with Ricoh theta S system can be extended to other dual-fisheye systems, such as GoPro Fusion camera; (2) a comparative analysis with other fisheye models proposed in the literature and other techniques for multi-camera calibration can be also performed; (3) a stochastic weighting of observation can be insert, since the fisheye images have non-uniform spatial resolution; (4) the equisolid-angle projection model can be used for 3D reconstruction using hyper-hemispherical observations; and (5) a full-mapping can be achieved combining multi-sensor data, such as aerial images, LiDAR data and multispectral and hyperspectral images. These are investigations that may contribute to further studies on hyper-hemispherical fisheye models, improving the quality of results in applications.

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