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Catadioptric stereo-vision system using a spherical mirror

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Abstract

In the computer vision field, the reconstruction of target surfaces is usually achieved by using 3D optical scanners assembled integrating digital cameras and light emitters. However, these solutions are limited by the low field of view, which requires multiple acquisition from different views to reconstruct complex free-form geometries. The combination of mirrors and lenses (catadioptric systems) can be adopted to overcome this issue. In this work, a stereo catadioptric optical scanner has been developed by assembling two digital cameras, a spherical mirror and a multimedia white light projector. The adopted configuration defines a non-single viewpoint system, thus a non-central catadioptric camera model has been developed. An analytical solution to compute the projection of a scene point onto the image plane (forward projection) and vice-versa (backward projection) is presented. The proposed optical setup allows omnidirectional stereo vision thus allowing the reconstruction of target surfaces with a single acquisition. Preliminary results, obtained measuring a hollow specimen, demonstrated the effectiveness of the described approach.

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Keywords: 3D acquisition; structured light scanning; catadioptric stereo vision system; spherical mirror projection model; internal geometries acquisition

1. Introduction

The 3D reconstruction of mechanical parts is widely used in many branches of modern manufacturing industry to create digital models. In general, the shape of an existing physical model can be retrieved by using contact techniques

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as in Hartig et al. (2012) , non-contact techniques as in Mian et al. (2015) or by exploiting multisensor approaches which integrate data deriving from different sensors as obtained by Barone et al. (2017) and Barone et al. (2017). Contact techniques make use of coordinate measuring machines or articulated arms, typically equipped with tactile probes, and provide accurate point-by-point measurements Hartig, Lin et al. (2012) . However, they only provide a limited number of measurements and are not suitable for the reconstruction of free-form shapes. On the other hand, non-contact techniques, as optical surface scanners (exploiting white light or laser light) or tomographic scanners, are able to perform full-field measurements. Among non-contact techniques, optical methods based on the triangulation principle provide full-field measurements with minimum user interaction Kevin (2013). Common arrangements are obtained by coupling a fringe projector with a single digital camera or two digital cameras assembled in a stereo rig. These solutions, however, are characterized by a limited field of view since projection and imaging devices must cover the same area. Catadioptric systems can be adopted to overcome this restriction. A catadioptric system is defined by the combination of single or multiple mirrors having different shapes (planar or curved) and lenses. The most used mirror shapes are those characterized by axial symmetry as spherical, parabolic, elliptical or hyperbolic, since they can cover the full azimuthal field of view. The viewed scene undergoes a transformation due to the reflection in the mirror. The projection of three-dimensional scene points to the corresponding two-dimensional points on the camera image plane can be obtained through a mapping function. The use of curved mirrors typically defines non-single viewpoint (non-SVP) sensors and introduces difficulties in the analytical modelling of the mapping function, which requires the calibration of the mirror geometry and pose with respect to the vision system Sturm et al. (2011). Stereo catadioptric configurations are required to provide the 3D reconstruction of a scene. Stereo vision is based on the common feature matching between two images taken from different positions. Depth is recovered by triangulating corresponding features on the images. Catadioptric omnidirectional stereovision can be obtained by using a single camera with at least two mirrors as in Fiala and Basu (2005) or in Jaramillo et al. (2016), two cameras and a single mirror as in Lin and Bajcsy (2003), two cameras and two mirrors as in Ragot et al. (2006) or in Boutteau et al. (2008). These configurations, however, define passive systems and are mainly used for robotic applications. When a 3D vision system is developed for metrological purposes, the passive stereo vision approach is not robust due to the difficulties in searching similar features in both images. For this reason, active approaches, based on the projection of structured patterns by a light emitter, are usually adopted. A catadioptric sensor based on a laser emitter, a camera and two hyperbolic mirrors is described in Orghidan et al. (2003). A similar approach is presented in Orghidan et al. (2006) where the pattern emitted by the laser diode is reflected by a conical mirror and a parabolic mirror is used to reflect the whole scene into the camera. A panoramic system composed of a white light projector, two parabolic mirrors and a digital camera is presented in Almaraz-Cabral et al. (2016). The system projects circular fringes and uses a temporal phase unwrapping technique to reconstruct the scene. However, this approach assumes that all the optical axes of the involved elements are coincident. Moreover, the projector must be calibrated in order to reduce the distortion influence.

In the present work, an active omnidirectional optical scanner has been developed by assembling two perspective digital cameras, a spherical mirror and a multimedia white light projector. The same mirror is used to reflect the structured patterns projected on the sphere by the light emitter and to reflect the 3D scene into the cameras, thus resulting in a more compact configuration. In the proposed approach, the projector is un-calibrated and not directly involved in the measurement process since the stereo triangulation is carried out by exploiting the two cameras. Spherical mirrors represent an attractive and practical solution to create catadioptric systems due to their low fabrication costs. The aim of the work is the definition of a non-contact system capable of 360-degree 3D reconstructions of internal cylindrical environments, which are typically characterized by accessibility restrictions. The adopted optical configuration defines a non-central catadioptric system. For this reason, a catadioptric camera model has been developed. An analytical solution to compute the projection of a scene point onto the image plane and vice-versa is presented. The calibration procedure follows a two-steps approach: firstly, a conventional calibration of the stereo rig (without the spherical mirror) is performed to determine intrinsic and extrinsic camera parameters. The mirror is then introduced in the system and an optimization process is carried out to determine the sphere radius and pose with respect to the cameras. Preliminary results obtained by acquiring a hollow cylinder with a conical housing demonstrated the effectiveness of the developed catadioptric stereo-vision setup.