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Structured light stereo catadioptric scanner based on a spherical mirror

S. Barone, P. Neri*, A. Paoli, A.V. Razionale

University of Pisa, Department of Civil and Industrial Engineering, Largo Lucio Lazzarino, 1, 56122 Pisa, Italy

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ABSTRACT

The present paper describes the development and characterization of a structured light stereo catadioptric scanner for the omnidirectional reconstruction of internal surfaces. The proposed approach integrates two digital cameras, a multimedia projector and a spherical mirror, which is used to project the structured light patterns generated by the light emitter and, at the same time, to reflect into the cameras the modulated fringe patterns diffused from the target surface. The adopted optical setup defines a non-central catadioptric system, thus relaxing any geometrical constraint in the relative placement between optical devices. An analytical solution for the reflection on a spherical surface is proposed with the aim at modelling forward and backward projection tasks for a non-central catadioptric setup. The feasibility of the proposed active catadioptric scanner has been verified by reconstructing various target surfaces. Results demonstrated a great influence of the target surface distance from the mirror's centre on the measurement accuracy. The adopted optical configuration allows the definition of a metrological 3D scanner for surfaces disposed within 120 mm from the mirror centre.

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1. Introduction

Recent advances in computer vision have allowed a widespread diffusion of non-contact 3D reconstruction systems that integrates imaging devices and fringe projection techniques [1]. These systems recover the shape of a target surface by exploiting the triangulation principle and the knowledge of the relative placement between a light source and an imaging device. Typical arrangements are obtained by coupling a fringe projector with a single digital camera or two digital cameras assembled in a stereo rig. In this latter case, the stripe projector is generally uncalibrated since not directly involved in the measurement process. A typical drawback of stereoscopic vision adopting conventional lenses is represented by the limited field of view. For this reason, multiple acquisitions are usually carried out from different views to reconstruct the overall shape of target objects. Moreover, conventional systems are not suitable for the acquisition of internal geometries since they are limited by accessibility and visibility restrictions for both cameras and projector. A practical solution to enhance the field of view of conventional cameras relies on the use of catadioptric systems defined by the combination of mirrors (catoptrics) and lenses (dioptrics). The use of external mirrors combined with digital cameras allows to define a broad range of solutions for computer vision applications. Catadioptric devices are used for vision-based tasks in driver assistance systems [2], robot and unmanned aerial vehicle navigation [3–5], 3D metrology applications [6,7]. Combinations of single or multiple mirrors having different shapes (planar or curved) are placed in front of one or more cameras to widen the field of view [8,9]. However, most of the mirrors used in catadioptric systems are characterized by axially symmetric shapes (spherical, parabolic, elliptical and hyperbolic) since they must cover the full azimuthal field of view. The viewed scene undergoes a transformation due to the reflection in the mirror. A mapping function enables the re-projection of 3D points on the scene to the corresponding 2D camera pixels. If the scene is observed from a single point in the space, the sensor has a unique centre of projection (single viewpoint (SVP)) and the mapping function is easy to be modelled and used. Nevertheless, the use of curved mirrors leads to central catadioptric systems (effective single viewpoint) only under severe constraints on the camera placement with respect to the mirror. On the other hand, non-SVP catadioptric systems increase the flexibility in the positioning of the imaging devices but introduce difficulties in the analytical modelling of the mapping function and approximations are introduced if central models are used [10]. In all the cases, curved mirrors must be calibrated, by determining their geometry and pose with respect to the vision system, especially if the system is developed for metrology purposes.

In this work, an omnidirectional Structured Light Stereo Catadioptric (SLSC) scanner has been developed by assembling two perspective digital cameras, a spherical mirror and a multimedia white light projector. The aim is the definition of a non-contact system capable of 360-degree 3D reconstructions of internal environments, which are typically characterized by accessibility restrictions. The adopted optical configuration defines a non-SVP catadioptric system. For this reason, a non-

* Corresponding author.
E-mail addresses: s.barone@ing.unipi.it (S. Barone), paolo.neri@dici.unipi.it (P. Neri), a.paoli@ing.unipi.it (A. Paoli), a.razionale@ing.unipi.it (A.V. Razionale).

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central catadioptric camera model has been developed. An analytical closed form solution to compute both forward projection (FP, from 3D to 2D) and backward projection (BP, from 2D to 3D) through the spherical mirror is presented. A multi-step optimization process is proposed to determine the sphere radius and pose with respect to the imaging system. A sensitivity analysis is also described, in order to assess the effects of various error sources on the system performances. The main contribution of the paper relies on the definition of a stereo optical setup, which is composed by two cameras. The use of a camera pair differentiates from the majority of the approaches existent in literature and allows to overcome the problem of the projector calibration, which is not a trivial task. Moreover, no constraints on the relative placement between the optical elements are required since a non-SVP catadioptric system is defined.

The feasibility of the proposed approach has been verified by acquiring some primitive shapes (planar, cylindrical and conical), assumed as reference geometries, and the overall surface of a hollow specimen. The experimental data allowed to assess both effectiveness and limitations of the developed active catadioptric stereo-vision system for metrological purposes.

2. Background

A catadioptric system uses a combination of lenses and mirrors properly configured to image a wider field of view with respect to conventional vision systems. Catadioptric systems can be primarily classified depending on how the imaging sensors capture light rays. When all the observed light rays converge into one point, called the focus, the vision system is characterized by a Single View Point (SVP). The use of SVP sensors is desirable since they respect the perspective projection law in mapping 3D object points to 2D image points. Perspective images can be then easily processed by adopting conventional computer vision techniques [11]. When light rays do not intersect in a single point, the imaging system does not maintain a single viewpoint and a locus of viewpoints (*caustic*) in the three-dimensional space is created. The locus of viewpoints depends on the geometrical properties of the camera, mirrors, lenses and their relative positioning.

SVP catadioptric systems may be assembled by adopting planar, conical, spherical, ellipsoidal, hyperboloid and parabolic mirrors. The use of a single planar mirror lacks practical value since the field of view is not enhanced. For this reason, multi-planar mirrors may be used [12]. Parabolic and hyperbolic shapes represent the most used solutions for SVP sensors [13]. However, the imaging components must obey single viewpoint constraints. For example, the conical mirrors have the SVP at the apex of the cone. This means that the camera's pinhole must be placed at the cone vertex [14]. Ellipsoidal mirrors can be used to build SVP systems if the pinhole and the viewpoint are placed at the two foci of the ellipsoid. In the case of the hyperbolic mirrors, the SVP constraint is satisfied when the pinhole and the mirror viewpoint are placed at the two foci of the hyperboloid. The parabolic shape is a solution for the SVP constraint if the image is formed by an orthographic projection and the viewing direction of the camera is parallel to the mirror axis. Spherical mirrors respect the SVP constraint only if the camera pinhole is placed at the sphere's centre [9]. All these solutions can be easily modelled by using central models. However, they require an accurate arrangement of the optical components (i.e., camera positioning with respect to the mirror) in order to respect the SVP constraint, and some of them are even useless because the SVP constraint leads to unpractical setups, as in the case of the spherical mirror. Furthermore, in the case of stereo systems with multiple cameras, it is difficult to respect the SVP constraint with both cameras. A greater flexibility in the design of catadioptric imaging systems can be obtained by relaxing the SVP constraint. This flexibility may be used to place camera and mirror in unconstrained positions and to achieve attractive qualities such as a greater spatial resolution and a wider field of view. It is indeed well known that one of the most limiting characteristics of omnidirectional vision sensors relies on their lower and non-uniform resolution with respect to perspective cameras [9]. In catadioptric systems, the image undergoes to a transformation that depends on the mirror shape. Moreover, stereo catadioptric configurations are required to provide the 3D reconstruction of a scene. Stereo vision is based on the matching of common features between two images taken from different placements. 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 [15,16], two cameras and a single mirror [17], two cameras and two mirrors [18,19]. These configurations, however, define passive systems and are mainly used for robotic applications. When a 3D vision system must be developed for metrological purposes, the passive stereo vision approach is not considered 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 [20]. A similar approach is presented in [13] 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. Panoramic sensors composed of a white light projector, two mirrors and a digital camera are presented in [6,21]. The system proposed in [6] uses parabolic mirrors and projects circular fringes with a temporal phase unwrapping technique to reconstruct the scene. However, this approach assumes that all the optical axes of the involved elements are coincident. The panoramic sensor proposed in [21] exploits hyperbolic mirrors and it is based on variable-frequency structured light and phase shifting to increase matching accuracies and measurement resolution. However, both the above described approaches rely on the calibration of the projector to reduce the distortion influence. A panoramic fringe projection system is also proposed in [7]. A stereo setup, composed of a LCD projector and a CCD camera, is combined with a concave conical mirror, a beam-splitter and an axicon to provide panoramic projection and 3D reconstruction. This setup, however, is strictly limited by the geometrical constraints in the relative positioning of the optical components.

In this paper, a Structured Light Stereo Catadioptric (SLSC) scanner has been developed by integrating a spherical mirror, two digital perspective cameras and a DLP projector. A multi-temporal Gray code phase shift profilometry (GCPSP) is used to encode and reconstruct the 360° scene by exploiting a sequence of vertical and horizontal light patterns projected by the video projector. The spherical mirror is used to project the structured light patterns generated by the light emitter and, at the same time, to reflect into the cameras the modulated fringe patterns diffused from the target surface. Technical literature reports few examples of stereo-camera catadioptric arrangements using a single mirror [17]. The aim of the present work is the definition of a non-contact system capable of omnidirectional 3D reconstructions of internal cylindrical environments, which are typically characterized by accessibility restrictions. The adopted optical configuration defines a non-central catadioptric system, thus no constraints on the relative placement of the optical elements are required. Moreover, the use of two cameras differentiates from the majority of the approaches existent in literature and allows to avoid the calibration of the projector since it is not directly involved in the measurement process. An analytical model has been developed to compute both forward and backward projection for a catadioptric system composed of a perspective camera and a spherical mirror. The stereo-camera calibration process follows a three-step 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. This first mirror calibration step is achieved by using a planar chessboard pattern acquired from different views. Finally, a calibration refinement is performed by acquiring a cylindrical surface to fine-adjust mirror radius and centre location. A sensitivity analysis has been carried out in order to determine the influ-

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