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Axial stereo-photogrammetry for 360° measurement on tubular samples

Katia Genovese[a,*], Carmine Pappalettere[b]

[a]Università degli Studi della Basilicata, Dipartimento di Ingegneria e Fisica dell'Ambiente, Viale dell'Ateneo Lucano 10, 85100, Potenza, Italy
[b]Politecnico di Bari, Dipartimento di Ingegneria Meccanica e Gestionale, Viale Japigia 182, 70126, Bari, Italy

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Abstract

This work presents a stereo-photogrammetry (SP) based procedure to perform whole-body measurements on tubular samples. Such a system is designed for future applications to the study of vascular wall mechanics. The use of a concave conical mirror surrounding the specimen makes it possible to capture the reflected 360° surface with a single snapshot moving neither cameras nor object. Then, according to 3-D computer vision principles, a stereo camera system retrieves control points depth information from image-pairs of the investigated surface. An axial-SP arrangement is selected since is more suitable for this specific application than the more popular lateral-stereo model.

In this paper, particular emphasis is given to a formulation taking into account even small camera misalignments. A calibration process based on optimization concepts is used together with a feature-based matching algorithm to efficiently find correspondence between highly distorted images reflected by the conical mirror.

Both theoretical and experimental analyses on calibrated samples demonstrated feasibility and accuracy of the proposed procedure.

Keywords: 360° measurements; Stereo-photogrammetry; Tubular samples

1. Introduction

Understanding and modeling vascular wall mechanics is a primary issue in the study of circulatory diseases. Although theoretical and numerical studies on arterial compliance are increasing in numbers, relatively little work has been documented on the use of non-invasive full-field imaging techniques for monitoring 3-D vascular wall deformations. Usually, 2-D video dimension analyzer (VDA) systems recover length and diameter variations during inflation/extension tests by tracking position changes of two couples of markers applied longitudinally and transversely onto blood vessel surface [1]. Strain determination then relies on the assumption of axisymmetric deformations. However, because of the highly anisotropic and inhomogeneous structure of vascular tissue, full-field evaluation of blood vessel deformation map should be achieved to properly model its mechanical response. Bi-plane video systems for 3-D measurements on vascular segments appeared just very recently [2]. However, still no whole-body reconstruction has yet been reported.

To address issues mentioned above, a stereo-photogrammetry (SP) based procedure for reconstructing whole 3-D shape of tubular samples is proposed in this paper. Besides other interesting applications, in fact, the present system can indeed be used for recovering whole deformation map of arterial wall under inflation-extension tests.

SP falls in the variety of full-field non-contact optical methods developed for 3-D topographical data measurements [3]. Most commonly, when 360° profiling of an object is required, measurements are carried out in two steps: first, object images are grabbed from different views (using a multi-camera system or a camera-turntable arrangement); then, all views are merged together into a main point cloud [4].

In this research, principles of SP and radial metrology are combined together into a system capable to perform 3-D whole-body measurements with a single snapshot. A concave conical mirror coaxial to the tubular sample captures the whole reflected surface of the specimen moving neither acquisition system nor object. Images are

*Corresponding author. Tel.: +39 0971 205146; fax: +39 0971 205160.
E-mail address: genovese@unibas.it (K. Genovese).

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recorded with a stereo-camera system and then processed, following SP principles, to locate the virtual image of a pattern applied onto the sample surface. Finally, once cone mirror geometry and position have been assessed through calibration procedure, a straightforward specular transformation recovers object shape from virtual point location map.

Similar arrangements based on radial metrology concepts have already been used for obtaining panoramic views over a wide range of resolutions. Panoramic annular lens [5] and concave mirrors [6], for example, can be used for highly sensitive measurements on internal and external axi-symmetric surfaces with digital correlation and speckle interferometry, respectively. At lower spatial resolution, curved mirrors are extensively used for building SP catadioptric sensors in robot-vision applications [7]. However, on authors' knowledge, a radial-SP system for measuring large deformations on tubular sample has not yet been reported in literature.

To perform SP measurements [8] it is necessary to properly process image-pairs of the area of interest as captured by two cameras. The procedure for estimating depth from homologous points coordinates is defined by the specific camera model. In this study, we choose an axial-stereo (AS) arrangement (where the two cameras share a common optical axis). In fact, this set-up has, especially for this specific application, some significant advantages over the most widely used lateral-stereo (LS) model [9].

The paper describes as camera model and image processing algorithms are selected for optimally dealing with the highly distorted and in-homogeneous images reflected by the conical mirror. A formulation of AS model accounting cameras unknown misplacements is derived and implemented within a calibration procedure relying on optimization concepts.

Both simulations and experimental tests served to evaluate validity and accuracy of the proposed method. System proved itself able to provide very accurate results in spite of inherent drawbacks of axial-stereo configuration. Whole 360° shape of calibrated samples have been reconstructed from single snapshot acquisitions thus avoiding time-consuming multiple acquisitions and merging procedures.

2. Theoretical

This section briefly outlines the AS model and the issues connected to its use in omnidirectional view systems.

2.1. The 360° stereo-photogrammetric system

2.1.1. The axial- stereo model

Stereo-vision [8] includes the following main phases:

- image acquisition;
- features extraction;
- image matching (solving the correspondence problem);
- depth determination from image-pairs according to the camera model equations.

In SP, the object is imaged by two cameras [10]. Many different camera models have been used for specific applications: converging or parallel camera optical axes; camera translation along optical axis; and rotating camera optical axis. The most widely used stereo camera arrangement found in literature is the lateral-model which simulates the human visual system. There is a variety of techniques based on this camera model, see [8,11] for a survey.

Once the camera model has been defined, and two images of the same scene obtained, it is necessary to locate the projections of the same physical point onto camera sensors (matching problem). In fact, according to the formulation of the specific camera model, depth information is derived from homologous points disparities (i.e. differences in the $x-y$ coordinates of corresponding points in the images planes). Image matching techniques can be divided into three major categories: area-based, feature-based and hybrid. Area-based algorithms use the local gray level distribution information to find the best match between a pair of images [12,13]. Feature-based algorithms compare specific characteristics extracted from image-pairs, such as centroids, edges, lines, corners and other regular shapes [14]. Hybrid approaches properly combine both area-based and feature-based algorithms.

Fig. 1a shows the optical set-up including a concave cone mirror, a beam splitter and two CCD cameras proposed in this research to perform 360° measurements. To image the sample mounted coaxially to the conical mirror, an SP rig with two cameras sharing a common optical axis is adopted. Fig. 1b illustrates the rationale behind AS model. The concave mirror surrounding the specimen forms a perfect virtual image point P behind mirror for each world point P′ on the sample surface within the field of view of the acquisition system.

According to the scheme of Fig. 1b, the two cameras should be aligned with the axis of the cone mirror. However, to avoid view occlusion, one camera is placed away by using a beam splitter yet practically maintaining the alignment with optical axis. It can clearly be understood from Fig. 1b, how image point position on each camera sensor changes according to different viewpoints and focal lengths and is directly related to the world point location. Such disparity permits to calculate world coordinates of point P from local coordinates information on point-pairs P_N and P_F in the two camera views. Once virtual location map is reconstructed based on SP equations, a reflection allows to recover position of the object surface point P′.

The AS arrangement is chosen for dealing with the highly distorted images reflected by conical mirror. Briefly, for an AS model, the two views are easier to be compared than those obtained from the more common LS