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Camera Models and Fundamental Concepts Used in Geometric Computer Vision

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Abstract

This survey is mainly motivated by the increased availability and use of panoramic image acquisition devices, in computer vision and various of its applications. Different technologies and different computational models thereof exist and algorithms and theoretical studies for geometric computer vision ("structure-from-motion") are often re-developed without highlighting common underlying principles. One of the goals of this survey is to give an overview of image acquisition methods used in computer vision and especially, of the vast number of camera models that have been proposed and investigated over the years, where we try to point out similarities between different models. Results on epipolar and multi-view geometry for different camera models are reviewed as well as various calibration and self-calibration approaches, with an emphasis on non-perspective cameras. We finally describe what we consider are fundamental building blocks for geometric computer vision or structure-from-motion: epipolar geometry, pose and motion estimation, 3D scene modeling, and bundle adjustment. The main goal here is to highlight the main principles of these, which are independent of specific camera models.

Contents

1

Introduction and Background Material

1.1 Introduction

Many different image acquisition technologies have been investigated in computer vision and other areas, many of them aiming at providing a wide field of view. The main technologies consist of catadioptric and fisheye cameras as well as acquisition systems with moving parts, e.g., moving cameras or optical elements. In this monograph, we try to give an overview of the vast literature on these technologies and on computational models for cameras. Whenever possible, we try to point out links between different models. Simply put, a computational model for a camera, at least for its geometric part, tells how to project 3D entities (points, lines, etc.) onto the image, and vice versa, how to back-project from the image to 3D. Camera models may be classified according to different criteria, for example the assumption or not of a single viewpoint or their algebraic nature and complexity. Also, recently several approaches for calibrating and using "non-parametric" camera models have been proposed by various researchers, as opposed to classical, parametric models.

In this survey, we propose a different nomenclature as our main criterion for grouping camera models. The main reason is that even so-called non-parametrics models do have parameters, e.g., the coordinates of camera rays. We thus prefer to speak of three categories: (i) A **global camera model** is defined by a set of parameters such that changing the value of any parameter affects the projection function all across the field of view. This is the case for example with the classical pinhole model and with most models proposed for fisheye or catadioptric cameras. (ii) A **local camera model** is defined by a set of parameters, each of which influences the projection function only over a subset of the field of view. A hypothetical example, just for illustration, would be a model that is "piecewise-pinhole", defined over a tessellation of the image area or the field of view. Other examples are described in this monograph. (iii) A **discrete camera model** has sets of parameters for individual image points or pixels. To work with such a model, one usually needs some interpolation scheme since such parameter sets can only be considered for finitely many image points. Strictly speaking, discrete models plus an interpolation scheme are thus not different from the above local camera models, since model parameters effectively influence the projection function over regions as opposed to individual points. We nevertheless preserve the distinction between discrete and local models, since in the case of discrete models, the considered regions are extremely small and since the underlying philosophies are somewhat different for the two classes of models.

These three types of models are illustrated in Figure 1.1, where the camera is shown as a black box. As discussed in more detail later in the monograph, we mainly use back-projection to model cameras, i.e., the mapping from image points to camera rays. Figure 1.1 illustrates back-projection for global, discrete and local camera models.

After describing camera models, we review central concepts of geometric computer vision, including camera calibration, epipolar and multi-view geometry, and structure-from-motion tasks, such as pose and motion estimation. These concepts are exhaustively described for perspective cameras in recent textbooks [137, 213, 328, 336, 513]; our emphasis will thus be on non-perspective cameras. We try to describe the various different approaches that have been developed for camera calibration, including calibration using grids or from images of higher level primitives, like lines and spheres, and self-calibration. Throughout

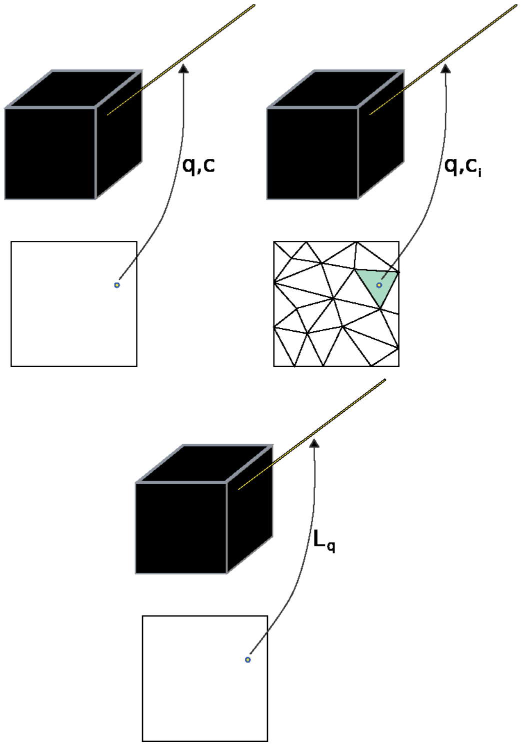

Fig. 1.1 Types of camera models. *Left*: For global models, the camera ray associated with an image point $\mathbf{q}$ is determined by the position of $\mathbf{q}$ and a set of global camera parameters contained in a vector $\mathbf{c}$. *Middle*: For discrete models, different image regions are endowed with different parameter sets. *Right*: For discrete models, the camera rays are directly given for sampled image points, e.g., by a look-up table containing Plücker coordinates, here the Plücker coordinates $\mathbf{L}_\mathbf{q}$ of the ray associated with image point $\mathbf{q}$.

this monograph, we aim at describing concepts and ideas rather than all details, which may be found in the original references.

The monograph is structured as follows. In the following section, we give some background material that aims at making the mathematical treatment presented in this monograph, self-contained. In Section 2, we review image acquisition technologies, with an emphasis on omnidirectional systems. Section 3 gives a survey of computational camera models in the computer vision and photogrammetry literature, again emphasizing omnidirectional cameras. Results on epipolar and multi-view geometry for non-perspective cameras are summarized in Section 4. Calibration approaches are explained in Section 5, followed by an overview of some fundamental modules for structure-from-motion in Section 6. The monograph ends with conclusions, in Section 7.

1.2 Background Material

Given the large scope of this monograph, we rather propose summaries of concepts and results than detailed descriptions, which would require an entire book. This allows us to keep the mathematical level at a minimum. In the following, we explain the few notations we use in this monograph. We assume that the reader is familiar with basic notions of projective geometry, such as homogeneous coordinates, homographies, etc. and of multi-view geometry for perspective cameras, such as the fundamental and essential matrices and projection matrices. Good overviews of these concepts are given in [137, 213, 328, 336, 513].

Fonts. We denote scalars by italics, e.g., s, vectors by bold characters, e.g., $\mathbf{t}$ and matrices in sans serif, e.g., A. Unless otherwise stated, we use homogeneous coordinates for points and other geometric entities. Equality between vectors and matrices, up to a scalar factor, is denoted by $\sim$. The cross-product of two 3-vectors $\mathbf{a}$ and $\mathbf{b}$ is written as $\mathbf{a} \times \mathbf{b}$.

Plücker coordinates for 3D lines. Three-dimensional lines are represented either by two distinct 3D points, or by 6-vectors of so-called Plücker coordinates. We use the following convention. Let $\mathbf{A}$ and $\mathbf{B}$ be two 3D points, in homogeneous coordinates. The Plücker coordinates of the line spanned by them, are then given as:

$$\begin{pmatrix} B_4\bar{\mathbf{A}} - A_4\bar{\mathbf{B}} \\ \bar{\mathbf{A}} \times \bar{\mathbf{B}} \end{pmatrix}, \tag{1.1}$$

where $\bar{\mathbf{A}}$ is the 3-vector consisting of the first three coordinates of $\mathbf{A}$ and likewise for $\bar{\mathbf{B}}$.

The action of displacements on Plücker coordinates is as follows. Let $\mathbf{t}$ and R be a translation vector and rotation matrix that map points according to:

$$\mathbf{Q} \mapsto \begin{pmatrix} \mathsf{R} & \mathbf{t} \\ \mathbf{0}^{\mathsf{T}} & 1 \end{pmatrix} \mathbf{Q}.$$

Plücker coordinates are then mapped according to:

$$\mathbf{L} \mapsto \begin{pmatrix} \mathsf{R} & \mathsf{0} \\ -[\mathbf{t}]_\times \mathsf{R} & \mathsf{R} \end{pmatrix} \mathbf{L}, \tag{1.2}$$

where $\mathsf{0}$ is the 3×3 matrix composed of zeroes.

Two lines cut one another exactly if

$$\mathbf{L}_2^\mathsf{T} \begin{pmatrix} \mathsf{0}_{3\times3} & \mathsf{I}_{3\times3} \\ \mathsf{I}_{3\times3} & \mathsf{0}_{3\times3} \end{pmatrix} \mathbf{L}_1 = 0. \tag{1.3}$$

Lifted coordinates. It is common practice to linearize polynomial expressions by applying Veronese embeddings. We use the informal term "lifting" for this, for its shortness. Concretely, we apply lifting to coordinate vectors of points. We will call "n-order lifting" of a vector $\mathbf{a}$, the vector $\mathcal{L}^n(\mathbf{a})$ containing all n-degree monomials of the coefficients of $\mathbf{a}$. For example, second and third order liftings for homogeneous coordinates of 2D points, are as follows:

$$\mathcal{L}^2(\mathbf{q}) \sim \begin{pmatrix} q_1^2 \\ q_1q_2 \\ q_2^2 \\ q_1q_3 \\ q_2q_3 \\ q_3^2 \end{pmatrix} \quad \mathcal{L}^3(\mathbf{q}) \sim \begin{pmatrix} q_1^3 \\ q_1^2q_2 \\ q_1q_2^2 \\ q_2^3 \\ q_1^2q_3 \\ q_1q_2q_3 \\ q_2^2q_3 \\ q_1q_3^2 \\ q_2q_3^2 \\ q_3^3 \end{pmatrix}. \tag{1.4}$$

Such lifting operations are useful to describe several camera models. Some camera models use "compacted" versions of lifted image point coordinates, for example:

$$\begin{pmatrix} q_1^2 + q_2^2 \\ q_1q_3 \\ q_2q_3 \\ q_3^2 \end{pmatrix}.$$

We will denote these as $\bar{\mathcal{L}}^2(\mathbf{q})$, and use the same notation for other lifting orders.

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