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Time-of-Flight Cameras

Principles, Methods and Applications

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Preface

This book describes a variety of recent research into time-of-flight imaging. Time-of-flight cameras are used to estimate 3D scene structure directly, in a way that complements traditional multiple-view reconstruction methods. The first two chapters of the book explain the underlying measurement principle, and examine the associated sources of error and ambiguity. Chapters 3 and 4 are concerned with the geometric calibration of time-of-flight cameras, particularly when used in combination with ordinary color cameras. The final chapter shows how to use time-of-flight data in conjunction with traditional stereo matching techniques. The five chapters, together, describe a complete depth and color 3D reconstruction pipeline. This book will be useful to new researchers in the field of depth imaging, as well as to those who are working on systems that combine color and time-of-flight cameras.

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Contents

Chapter 1
Characterization of Time-of-Flight Data

Abstract This chapter introduces the principles and difficulties of time-of-flight depth measurement. The depth images that are produced by time-of-flight cameras suffer from characteristic problems, which are divided into the following two classes. First, there are systematic errors, such as noise and ambiguity, which are directly related to the sensor. Second, there are nonsystematic errors, such as scattering and motion blur, which are more strongly related to the scene content. It is shown that these errors are often quite different from those observed in ordinary color images. The case of motion blur, which is particularly problematic, is examined in detail. A practical methodology for investigating the performance of depth cameras is presented. Time-of-flight devices are compared to structured-light systems, and the problems posed by specular and translucent materials are investigated.

Keywords Depth-cameras · Time-of-Flight principle · Motion blur · Depth errors

1.1 Introduction

Time-of-Flight (ToF) cameras produce a *depth image*, each pixel of which encodes the distance to the corresponding point in the scene. These cameras can be used to estimate 3D structure directly, without the help of traditional computer-vision algorithms. There are many practical applications for this new sensing modality, including robot navigation [31, 37, 50], 3D reconstruction [17], and human–machine interaction [9, 45]. ToF cameras work by measuring the phase delay of reflected infrared (IR) light. This is not the only way to estimate depth; for example, an IR *structured-light* pattern can be projected onto the scene, in order to facilitate visual triangulation [44]. Devices of this type, such as the Kinect [12], share many applications with ToF cameras [8, 33, 34, 36, 43].

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The unique sensing architecture of the ToF camera means that a raw depth image contains both systematic and nonsystematic bias that has to be resolved for robust depth imaging [11]. Specifically, there are problems of low depth precision and low spatial resolution, as well as errors caused by radiometric, geometric, and illumination variations. For example, measurement accuracy is limited by the power of the emitted IR signal, which is usually rather low compared to daylight, such that the latter contaminates the reflected signal. The amplitude of the reflected IR also varies according to the material and color of the object surface.

Another critical problem with ToF depth images is *motion blur*, caused by either camera or object motion. The motion blur of ToF data shows unique characteristics, compared to that of conventional color cameras. Both the depth accuracy and the frame rate are limited by the required integration time of the depth camera. Longer integration time usually allows higher accuracy of depth measurement. For static objects, we may therefore want to decrease the frame rate in order to obtain higher measurement accuracies from longer integration times. On the other hand, capturing a moving object at fixed frame rate imposes a limit on the integration time.

In this chapter, we discuss depth-image noise and error sources, and perform a comparative analysis of ToF and structured-light systems. First, the ToF depth-measurement principle will be reviewed.

1.2 Principles of Depth Measurement

Figure 1.1 illustrates the principle of ToF depth sensing. An IR wave indicated in red is directed to the target object, and the sensor detects the reflected IR component. By measuring the phase difference between the radiated and reflected IR waves, we can calculate the distance to the object. The phase difference is calculated from the relation between four different electric charge values as shown in Fig. 1.2. The four phase control signals have 90 degree phase delays from each other. They determine the collection of electrons from the accepted IR. The four resulting electric charge values are used to estimate the phase difference t_d as

$$t_d = \arctan\left(\frac{Q_3 - Q_4}{Q_1 - Q_2}\right) \tag{1.1}$$

where Q_1 to Q_4 represent the amount of electric charge for the control signals C_1 to C_4, respectively [11, 20, 23]. The corresponding distance d can then be calculated, using c the speed of light and f the signal frequency:

$$d = \frac{c}{2f}\frac{t_d}{2\pi}. \tag{1.2}$$

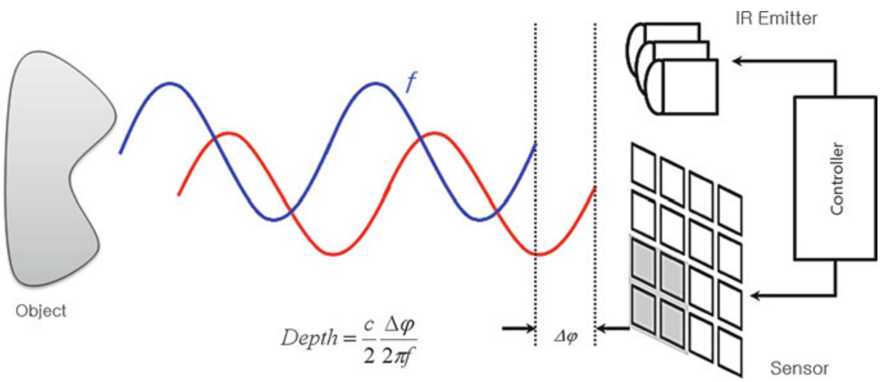

Fig. 1.1 The principle of ToF depth camera [11, 20, 23]: the phase delay between emitted and reflected IR signals are measured to calculate the distance from each sensor pixel to target objects

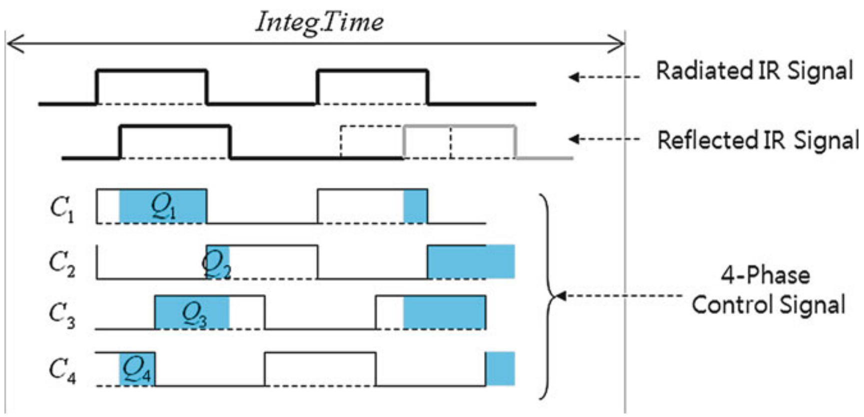

Fig. 1.2 Depth can be calculated by measuring the phase delay between radiated and reflected IR signals. The quantities Q_1 to Q_4 represent the amount of electric charge for control signals C_1 to C_4 respectively

Here, the quantity $c/(2f)$ is the maximum distance that can be measured without ambiguity, as will be explained in Chap. 2.

1.3 Depth-Image Enhancement

This section describes the characteristic sources of error in ToF imaging. Some methods for reducing these errors are discussed. The case of motion blur, which is particularly problematic, is considered in detail.