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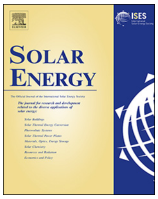

Reconstructing atmospheric cloud particles from multiple fisheye cameras

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ABSTRACT

In this article we address the problem of accurately reconstructing the 3D position and short-term motion of atmospheric cloud using passive instruments. The proposed system is based on multiple fish-eye cameras that capture daylight sky images in a synchronous manner. After introducing the inherent difficulties of the task, we propose novel methods for improving robustness and accuracy in the given application scenario. We emphasize the effectiveness of a multi-view (in our example a trinocular) camera system over a stereo camera pair with respect to reliability and precision of both 3D position and motion reconstructions. During the evaluation of the methods we address limitations and possible effective parametrization of the system, including the positioning of the cameras.

1. Introduction

1.1. Motivation and background

The knowledge of the actual and future position of atmospheric clouds holds well understood benefits for meteorology and beyond. However, the different applications have a wide range of accuracy requirements and this affects the instrumentation required to solve the task. We address here an application that has a high demands on both position accuracy and short-term motion estimation of all visible cloud parts. While we target the highest possible accuracy, it is also a necessity to have an automatic system that is capable of robust operation in an unattended manner and has a limited cost. These sometimes contradictory requirements form the motivation for this work.

1.2. Active systems

Atmospheric cloud particles visibly to the human eye can be detected by a number of different sensors. Water that has already changed state into liquid is detectable by RADAR sensors (Mead et al., 1994; Kollias et al., 2007) and its motion can be reliably tracked on the longer term. But RADAR systems are limited in resolution and most importantly the water in liquid state is only part of the visible cloud. Most of the water in clouds have not yet changed into liquid before blocking light and becoming visible. In this respect Laser based technologies, like LiDAR systems (Bosch and Kleissl, 2013) prove more reliable results. On the down side, the density of 3D point cloud yielded by a LiDAR system is interconnected with its price, making a high quality LiDAR rather expensive. Also, high resolution data acquisition is time consuming which is a problem on quickly changing scenes. Beside the scanning time, it may also be a problem that the returned data is lacking color information that could help verification of the reconstructed data. Finally active systems suitable for this application are usually subject to regulatory licensing of the tranmsitter which can be expensive, difficult and even impossible to obtain.

1.3. Passive systems

Since atmospheric clouds reflect light in the visible spectrum, passive systems are also suitable for detecting them. There are several passive solutions available for reconstructing atmospheric clouds (Huang et al., 2013; Peng et al., 2015; Peng et al., 2016; Chow et al., 2011; Urquhart et al., 2012; Chow et al., 2015; Katai-Urban et al., 2016). These systems mostly include cameras or other light sensors and optical elements (like the Total Sky Images (TSIs) (Chow et al., 2011)).

For global scale and larger time intervals, satellite images are often used to estimate cloud motion and formations. Satellite imaging-based cloud tracking has a long history. Usually some cross-correlation based techniques were used to track larger regions of clouds through time (Hamill and Nehrkorn, 1993). In combination with a series of heuristics and filtering spurious tracks, this method proved to be quite robust. As computation capabilities increased studies showed that optical flow can

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be a viable alternative (Bresky and Daniels, 2006) to cross-correlation techniques.

However, satellite-imaging based methods are not designed to operate on time scales shorter than 15 min and for localized ground surface irradiation estimation, *i.e.* areas of a few square kilometers (*e.g.* to provide detailed meteorological forecast for smaller agricultural sites, or for solar arrays, where fluctuations in power have to be predicted). For such cases cloud tracking requires ground-based instruments. Since most active devices are expensive (such as LiDAR ceilometer), substantial research was put into the more cost-effective solutions such as the TSI and different fish-eye systems. It must be noted though, that TSIs are usually lower-resolution and by using a dome shaped mirror, it is typically sensitive to changing light conditions. In addition a mechanical sun blocking device often obstructs the region of must interests around the sun. Using High Definition fish-eye cameras (Gauchet et al., 2012) is a promising alternative to estimate cloud motion in short time windows and more localized areas.

1.4. Previous work

Algorithms processing camera images either use a cross-correlation based technique (Huang et al., 2013), apply sparse (Wood-Bradley et al., 2012) or dense (González et al., 2013; West et al., 2014) optical flow to track clouds in time. Optical flow methods can also be used to apply temporal information to segmentation, then robustly track the larger segmented blocks of clouds (Chauvin et al., 2016) using techniques similar to the cross-correlation based ones. Generally, correlation based techniques are usually extensions to pixel-based, optical flow techniques.

Studies originated from University of California San Diego (UCSD) related to this topic, as time progressed, first used a cross-correlation based technique (Chow et al., 2011), then gradually converted to optical flow more extensively in their works. In their more recent work (Chow et al., 2015), they found a variational optical flow approach to be superior to template-matching, still they also found that by simply grouping pixels via sub-sampling, tracking and motion vectors become more robust. They also developed the so-called Clear Sky Library (Chow et al., 2011) technique for cloud-background separation. To minimize the effect of obstruction, they employed multiple cameras (Urquhart et al., 2012), combining images into a single larger map.

Researchers at the Brookhaven National Laboratory, U.S. Department of Energy use multiple high-definition cameras with fish-eye lenses as sky imagers. To cancel the effects of abnormal exposure and further correct spurious classification and tracking (Peng et al., 2015; Peng et al., 2016) they incorporate spatial and temporal correlations through multiple time frames and sky imagers. For the sake of more robust tracks they also applied multiple scales of feature extraction. In a recent work (Peng et al., 2016) they constrained the optical flow field using block-based grouping.

Approaches involving simpler regressive models are often sufficient for short-term solar irradiance prediction for specific use-cases. To further improve prediction intervals and accuracy, some studies apply more complicated machine learning techniques or neural networks (González et al., 2013; West et al., 2014) and support vector machines (Peng et al., 2015).

1.5. Overview of the paper

In this paper we present a three camera system including camera setup and processing workflow. The article focuses on the use of multiple-cameras with the goal of reconstructing 3D position and motion of atmospheric cloud particles. In Section 2 the camera setup is discussed, followed by application related problems in Section 3 and the specialized reconstruction and motion detection pipeline tailored for atmospheric clouds in Section 4. In Section 5 we emphasize the benefits of multiple camera systems and present a novel way to exploit data from multiple cameras. Lacking real world ground truth data, we use synthetic evaluation methods described in Section 6. The properties of the multi-camera system are discussed in Section 7 addressing the question of the baseline distance, reliability, accuracy and eventually demonstrating sample results from real cloud images. This is followed by future works in Section 8 acknowledgment section.

2. Camera setup

As mentioned in the introduction, many different sky imaging systems have been proposed before. Our approach is to apply a ground based passive multi-camera system to capture clouds on the whole sky. A stereo system has recently been proposed (Katai-Urban et al., 2016), where two fish-eye cameras were applied to capture wide field of view (FOV) stereo images. This system has now been extended to a multi-view camera system with adding an extra fish-eye camera.

To capture clouds throughout the observed sky a special type of imaging system is required. The most efficient solution is to apply wide FOV cameras that are able to observe the sky 360° horizontally and 180° vertically. These so-called omni-directional optical systems can be divided into two types: dioptric and catadioptric systems. Catadioptric systems consist of mirrors and lenses and are usually equipped with a downward-looking camera (see Fig. 1). These systems have a blind spot (behind the camera) and thus are not ideal for observing the whole sky. Dioptric systems, on the other hand, use an upward-looking camera equipped with a fish-eye lens that provide a large FOV without a blind spot but often have lower resolution on the sides of the image. Note that cameras with Fisheye lens are non-central projective systems (*i.e.*, not having a single focal center), however, are usually considered as central-projective (Sturm et al., 2011; Scaramuzza et al., 2006).

2.1. Geometry

To use a camera system for reconstruction purposes, an appropriate model is required describing the projection mapping camera world points to points on the image plane. The Pinhole camera is the most simple and most commonly used model in computer vision, that

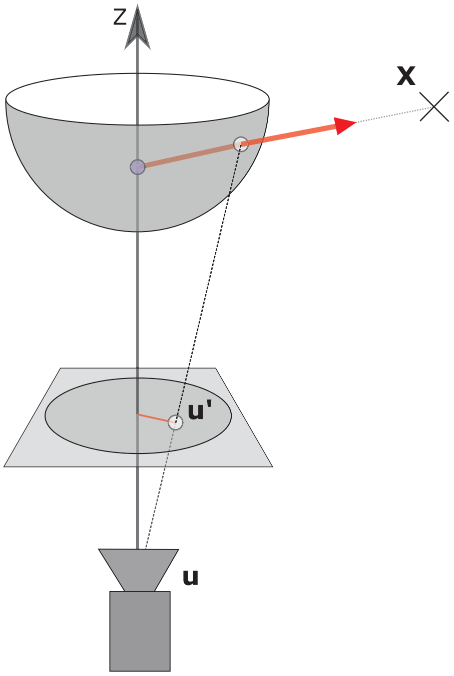

Fig. 1. A depiction of the camera model proposed by Scaramuzza et al. (2006). For each world point **X**, the ray from the mirror center to **X** is mapped to projective camera image point **u**.