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A hybrid approach to estimate the complex motions of clouds in sky images

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Tracking the motion of clouds is essential to forecasting the weather and to predicting the short-term solar energy generation. Existing techniques mainly fall into two categories: variational optical flow, and block matching. In this paper, we summarize recent advances in estimating cloud motion using ground-based sky imagers and quantitatively evaluate state-of-the-art approaches. Then we propose a hybrid tracking framework to incorporate the strength of both block matching and optical flow models. To validate the accuracy of the proposed approach, we introduce a series of synthetic images to simulate the cloud movement and deformation, and thereafter comprehensively compare our hybrid approach with several representative tracking algorithms over both simulated and real images collected from various sites/imagers. The results show that our hybrid approach outperforms state-of-the-art models by reducing at least 30% motion estimation errors compared with the ground-truth motions in most of simulated image sequences. Moreover, our hybrid model demonstrates its superior efficiency in several real cloud image datasets by lowering at least 15% Mean Absolute Error (MAE) between predicted images and ground-truth images.

1. Introduction

The variability and intermittency of generating solar power generation have become one of the biggest obstacles in integrating solar energy into the grid, while maintaining its stable operation (Hanley et al.). To mitigate the volatility of solar power, various solutions have been proposed, such as backup generators, battery reserves, and power system scheduling and dispatches. However, the effectiveness of these solutions largely depends on the accuracy of forecasting in advance the fluctuation of solar power. This need gives rise to a series of research projects in modeling and predicting solar irradiance. As clouds are the primary cause of the intermittency of solar irradiance and the correlated output of a PV system, predicting the variability of solar irradiance essentially becomes an effort to estimate the movement and properties of clouds, in other words, cloud tracking based on current information, and then to create a solar irradiance model from the predicted properties of the clouds (Hoff and Perez, 2012; Lave and Kleissl, 2013).

Over the past several decades, scientists have utilized remote sensing technology, for example, geostationary satellite imaging, to model and track clouds, and forecast solar irradiance (Escrig et al., 2013; Stuhlmann et al., 1990; Peng et al., 2013). Given the orbit of satellites, these approaches usually provide mid-term forecasts with a time horizon between half hour to six hours, and a spatial resolution of several kilometers. On the other hand, an ever-growing number of distributed roof-top solar panels and smart storage solutions in smart-grids operate in a much shorter time horizons and a smaller spatial resolution than that offered by satellite imagery, and so engenders a pressing need for short-term solar forecasts that predict minutes- or even seconds-ahead solar availability and variability. A promising technique to satisfy the requirement of tracking clouds and predicting solar activities at such a high resolution is the usage of ground-based sky imaging systems. In contrast to satellite imagery systems, the sky imager can visualize local clouds from the ground level in real time, and provide a high spatial resolution of sub-kilometers. Consequently, its output images are widely used for estimating the localized cloud fraction (Long et al., 2006; Pfister et al., 2003) and for

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analyzing the clouds' characteristics (e.g. opaqueness) (Shields et al., 1993; Singh and Glennen, 2005). More recently, sky imagers, coupled with various cross-domain techniques in the fields of computer vision and machine learning, offer an effective approach to extract the image-based features of clouds, identify their types, estimate their base height, and determine the vertical cloud layers via the clustering technology (Kazantzidis et al., 2012; Savoy et al., 2015; Nguyen and Kleissl, 2014; Peng et al., 2014). Based on the image features extracted and the results of cloud tracking, ground-based imagers gain a remarkable momentum recently to forecast solar irradiance within the range between half minute and up to thirty minutes (West et al., 2014; Bernecker et al., 2014; Yang et al., 2014), which precisely provides a complementary capability to those satellite-based approaches.

The solar forecast systems based on satellites and/or ground-based sky imagers essentially try to predict solar occlusion effect. The model usually involves identification of sun-occlusion pixels associated with ground measurements and estimation of cloud movement to predict the presence of clouds in near future (Chow et al., 2011). Consequently, having an accurate estimation of the cloud's motion is essential to various prediction models that utilize different imagers and target various forecast horizons (Chow et al., 2011; Huang et al., 2012; Haupt and Kosovic, 2015; Xu et al., 2015; Xu et al., 2015).

1.1. The limitations with current approaches

Among the techniques of tracking the motions of clouds, block matching and optical flow (OF) are applied widely to various types of imagery, including ground-based cameras and satellites.

Block matching technique takes a collection of pixels (i.e., a block) as a tracking unit, has the ability to utilize regional information, and thereby, is sufficiently robust to image noise and brightness variations within images. If the underlying motions consist of only translative velocity, and do not involve shearing and scaling, a block-matching approach can faithfully represent the true movements of clouds (Huang et al., 2011). However, the majority of block-matching approaches employ pre-defined blocks with a fixed size and position, i.e., a mesh or grid in an image (Hamill and Nehrkorn, 1993; Chow et al., 2011). Consequently, this type of block-matching approach is sensitive to the block's segmentation and an incorrect segmentation in an image can compromise its accuracy. Because non-rigid clouds have a variety of shapes and positions that invalidate any pre-defined segmentation, the performance of these block-based methods is inconsistent over the streams of images from the camera. Even with the assignment of dynamic blocks based on the cloud mask in a sky image (Peng et al., 2014), the performance of the block matching algorithm still deteriorates when multiple pieces of cloud reside within the same block. Many recent methods adopt a hierarchical block structure to track block-wise motions, and apply post-process filtering and interpolating to the tracking outputs (Huang et al., 2011; Mori and Chang). Nevertheless, with these approaches, only a limited improvement is attained, and it still relies on predefined block segmentation and the tedious tuning of block size and position.

On the other hand, optical flow (OF) addresses the motion tracking problem at a lower level than does block-matching. It enables to extract pixel-wise motion through variational methods that first define an energy-like objective function, assume the constancy of brightness cross images, and obtain the solution via minimizing the objective function. Compared to the block-matching approach, the OF model is flexible and can accurately represent complex 3-dimensional motions, such as rotation and scaling, at the pixel level (Héas et al., 2007; Héas and Mémin, 2008). However, it is sensitive to image noise and the variation in brightness, both of which are quite common in sky images. Another issue is that for texture-less regions or large-motion objects (e.g. fast-moving clouds in sky imagery), the accuracy of OF may drop significantly due to the lack of information (Brox and Malik, 2011). Even with the smoothness term (Golemati et al., 2012) or a regional mask (Wood-Bradley et al., 2012) that incorporate the surrounding information, current OF approaches still neglect the important features, such as the clouds' distribution and the multiple cloud layers, each of which has its own motion. Due to the multi-resolution image processing requirement and iterative optimization scheme, it usually take minutes or even longer time for OF approaches to extract motion field even from low-resolution images (Sun et al., 2014). Consequently, latency becomes one of the biggest concerns to an OF method and limits its application in short-term or real-time cloud motion tracking with high-resolution images.

1.2. Contributions

To fully address the problem of tracking cloud motions, we introduce existing state-of-the-art techniques of both block matching and optical flow in Section 2, and detail seven classic models that have already been applied to estimate cloud motions in sky imagery in Section 3. With observed advantages and disadvantages of prior approaches, in Section 4, we propose an innovative hybrid method that combines both block matching and optical flow to avoid their individual weaknesses and to mutually enhance each other's performance. In summary, we list our contributions in this paper as follows:

1. *Extracting dominant motion patterns*. To incorporate information of cloud layers into motion estimation, we attain the dominant motion vectors from block-wise motions to eliminate outliers and generate motion layers to constrain the optical flow (Sections 4.1 and 4.2).
2. *Formulating a novel optical flow model*. We devise a new OF energy-like function to ensure that optical flow is consistent with the regional trend of cloud motions and at the same time allows small perturbations to track localized deformation in clouds. Afterward, we apply an iterative approach to efficiently minimize the complex objective, and also introduce customized filters to further refine the resulting motions (Section 4.3).
3. *Evaluating our model on simulated and real datasets*. To validate the effectiveness of the tracking methods, we design a comprehensive simulation framework to incorporate translative cloud motions, shape deformation, and various levels of noises into synthetic sky images; then we evaluate our model under these circumstances with the known ground truth. Furthermore, we apply our model to real images collected from various imaging systems and vet its performance in real-world applications (Section 5).

2. Related works

Many motion-tracking techniques have been proposed to detect the motion of objects in terms of the pixel-wise movement across different images. However, only a few of them can be used to track cloud motion because of its non-rigid shape and formation. In general, the cloud motion vectors are important to numerical weather prediction models, and usually are obtained from satellite images (Leese et al., 1970; Cote and Tatnall, 1995; Evans, 2006; Corpetti et al., 2008). With the advent of inexpensive digital cameras and the emerging need for solar forecast with the fine granularity that is beyond the spatio-temporal resolution of satellite images, recent researches focused on using these ground-based cameras to track the very short-term motions of clouds (Wood-Bradley et al., 2012; Huang et al., 2013; Chow et al., 2011). These methods fall into three main categories based on the scale and tracking criterion