Autonomous Flight with Robust Visual Odometry under Dynamic Lighting Conditions

1. Introduction

Autonomous aerial robots that are designed to perform tasks without direct human remote control rely on accurate state information. Due to the limitations of GPS, vision-based state estimation so called visual odometry (VO) has been investigated to offer a less expensive solution with up to centimeter-level accuracy without sacrificing too much payload. Unlike autonomous ground vehicle navigation, small autonomous aerial robots pose a challenge in applying VO because VOs for the aerial robots have to compute sufficiently fast and accurate position estimates to maintain active control at high refresh rate and avoid failure.

In this work, we focus on robustness of VO for autonomous flight of the aerial robots. Although the accuracy and speed have been main objectives of many VO researches, the robustness to external environmental changes has not been addressed much. Especially, light changes in an image, including highlights, shadows caused by the changes of the camera viewing angle, unpredictable changes of light source, and the automatic exposure control, are inevitable phenomena that the aerial robots must deal with in practice. It is well known that direct VO methods, which perform state estimation using image brightness values, are very vulnerable to light variations, but the robustification to light changes still remains a challenge.

To address these issues, we propose *a robust direct visual odometry algorithm* that enables reliable autonomous flight of the aerial robots even in light-changing environments (see Fig. 1). The contributions of the paper can be summarized as follows.

- We present a novel direct VO algorithm that is robust under challenging lighting environments by including local affine parameters for estimating irregular illumination changes.
- We integrate a motion prior from the feature-based method into the direct approach for stable motion estimation, and analyze its usefulness in terms of convergence property.
- We demonstrate a real-time system enabling autonomous flights of the aerial robot in environments with irregular illumination changes.

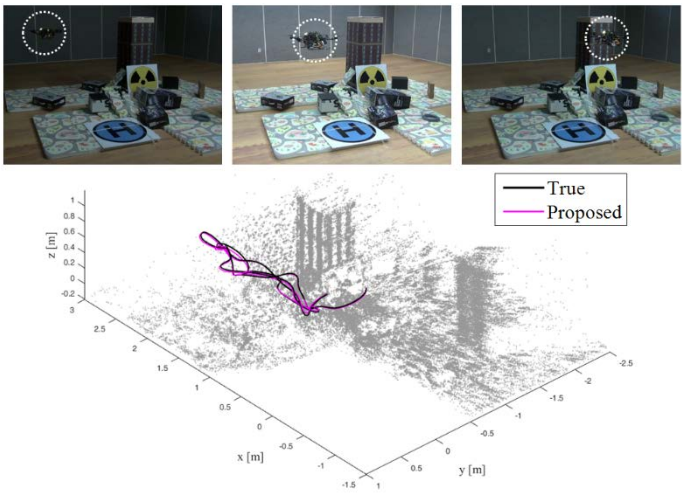

Fig. 1. Hexacopter aerial robot used in our autonomous flight experiments with varying light conditions by turning on and off the lights repeatedly.

2. Visual Odometry Pipeline

Our proposed VO method firstly estimates the motion of the camera using the feature-based information as shown in Fig. 2.

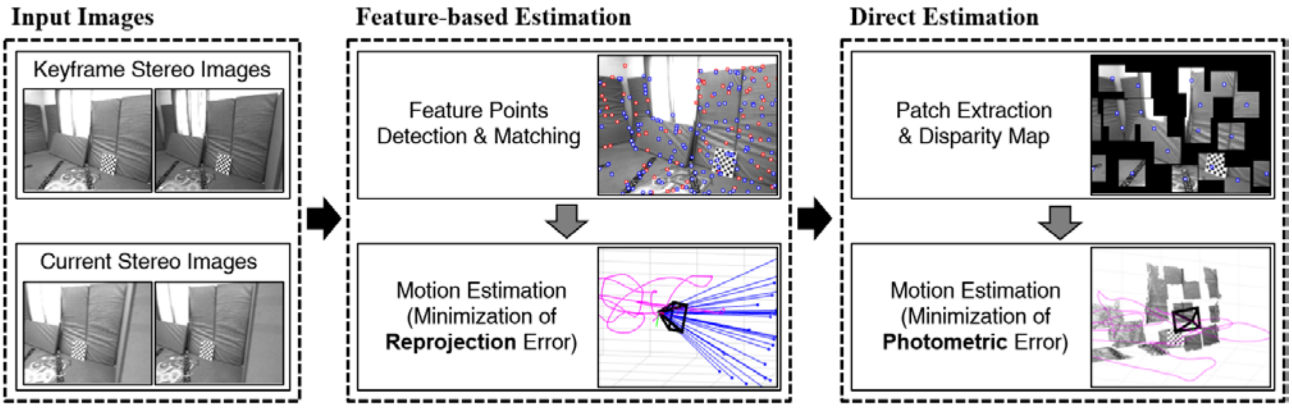

Fig. 2. Overview of the proposed stereo visual odometry pipeline.

The stereo image pairs from the two consecutive image frames are passed to the blob and corner masks to extract the feature points. We seek the optimal camera motion that minimizes the sum of squared left and right reprojection errors in the random sample consensus (RANSAC).

The 6-DoF camera motion from the feature-based estimation is just used as the motion prior of the illumination-robust direct visual odometry, which minimizes modified photometric error as follows:

$$r_{ij}(\boldsymbol{z}) = \lambda_i I_i^k\left(w\left(\xi, x_{ij}^*\right)\right) + \delta_i - I_i^*\left(x_{ij}^*\right) \quad (1)$$

$$\boldsymbol{z} \equiv [\xi^T, \lambda_1, \delta_2, \cdots, \lambda_m, \delta_m] \in \mathbb{R}^{6+2m}$$

where I_i^k is the i-th image patch from the gray-scale image at time step k. A 2D pixel point in I_i^k is denoted with x_{ij}^k where the subscript ij represents the pixel index j in the i-th image patch. ξ is relative motion of the camera between $\{C^k\}$ at time step k and $\{C^*\}$ at keyframe. λ_i and δ_i denote the illumination change model parameters for explaining

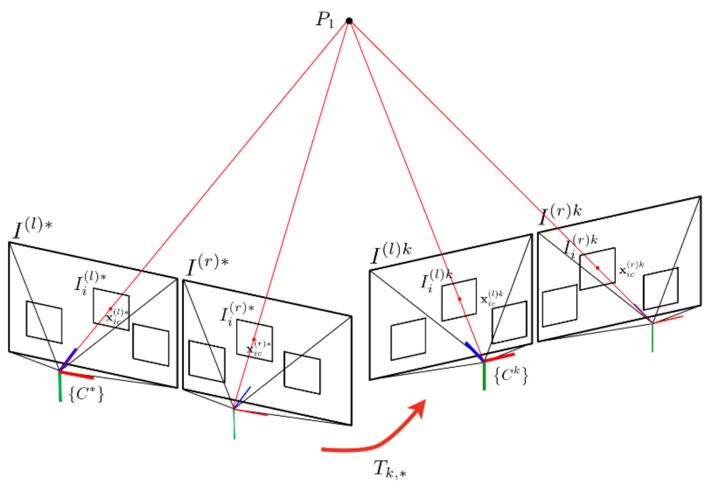

Fig. 3. Patch-based illumination invariant visual odometry.

contrast and brightness change of the i-th image patch. Thus, $\boldsymbol{z}$ is the integrated new model parameter vector consisting of the relative motion of the camera and the illumination change model parameters per each patch as illustrated in Fig. 3. The optimal model parameter $\boldsymbol{z}^*$, which minimizes the weighted sum of squared modified photometric errors can be obtained by iteratively solving the following non-linear weighted least square problem:

$$\boldsymbol{z}^* = \arg\min_{\boldsymbol{z}} \sum_{i=1}^{m} \sum_{j=1}^{n} W\left(r_{ij}\right) r_{ij}^2(\boldsymbol{z}) \tag{2}$$

where m and n are the number of patches and pixels, and W is the weighting function for robustness against outliers. To solve the nonlinear optimization in Eq. (2), the Gauss-Newton method is employed. The moving trajectory of the stereo camera rig can be obtained by concatenating the frame-to-keyframe motion estimation results incrementally.

3. Experimental Results

We show the potential of the proposed method with two different experiments. First, we demonstrate the performance of the proposed VO compared to other VO methods in the stairway where the natural illumination changes occur due to sunlight, automatic exposure control of the camera. In Fig. 4, the 80 m trajectory going up the stairs from the 1st to 6th floor of a building is visualized with three different views: top, front, and right side. The top view of the estimated trajectory shows the overlapped, consistent motion estimation result of the proposed method (magenta) while other estimated trajectories gradually diverge from the initially estimated loop. The side and front views of the stairway also support the high consistency of the proposed method compared with other VO methods.

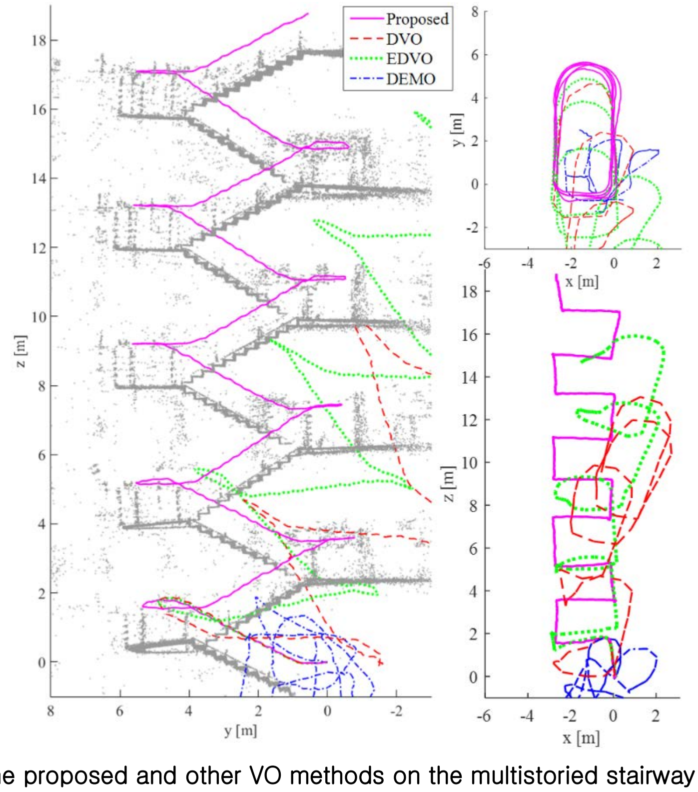

Fig. 4. Comparison of the proposed and other VO methods on the multistoried stairway from the 1st to 6th floor. The figure shows the side (left), front (right down), and top (right up) views of the estimated trajectories in the ascending stairway.

We also run our VO approach onboard an aerial robot, and used it to fly autonomously in challenging conditions like switching on and off the light in a low-lit room as illustrated in Fig. 1 and 5. The proposed illumination-robust VO algorithm allows the autonomous aerial robot to estimate its 6-DoF pose even in an environment where sudden and partial light variations occur frequently, as demonstrated in Fig. 5. We performed the flight experiments while lights in the room are turned on and off repeatedly and randomly, causing sudden and irregular illumination changes in the images as shown in the fourth row of Fig. 5. When the lights are turned on and off, the model parameters of the affine illumination change model in Eq. (1) are changed to compensate for the sudden and irregular illumination changes. Thanks to such compensation of the lighting changes, the estimated trajectory with the proposed VO method is qualitatively similar to the ground truth trajectory obtained from Vicon motion capture system. The gray dots in Fig. 1 are 3D reconstructed feature points used in the proposed method, showing the consistently reconstructed obstacles and objects.

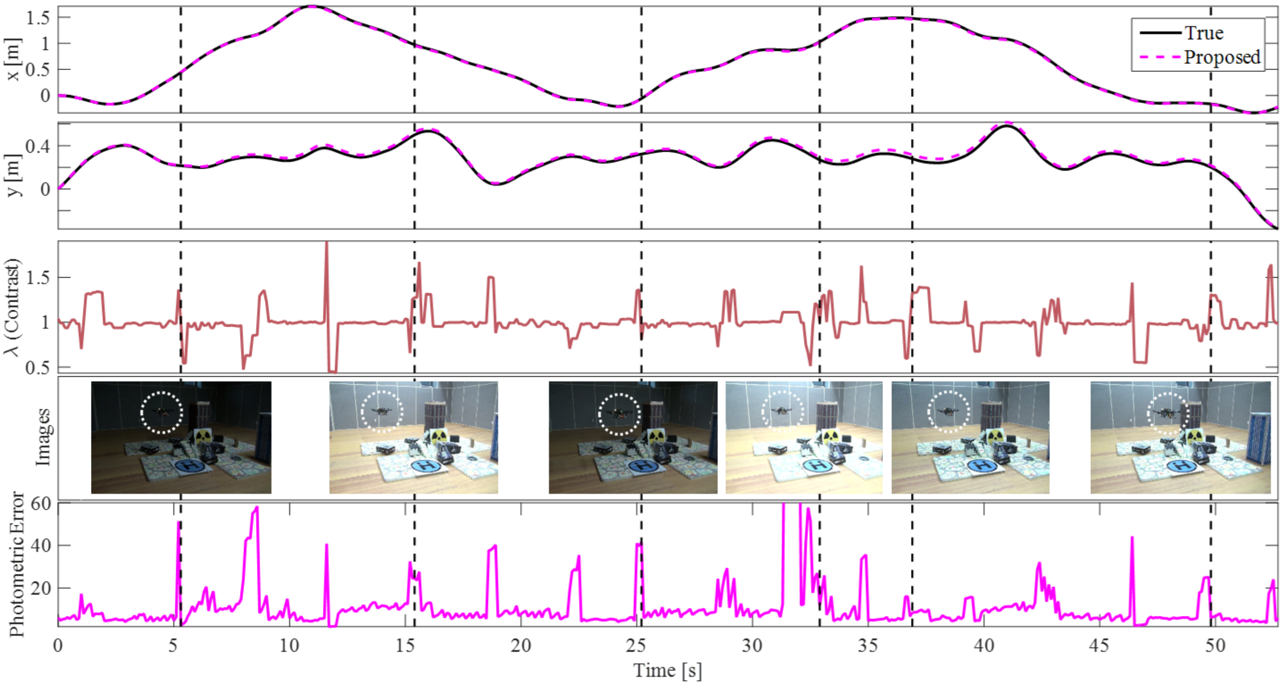

Fig. 5. Flight experiment results in a light-changing environment where lights are turned on and off repeatedly. The dotted vertical lines denote the time instants at which each snapshot is captured. We plot the changes of the estimated contrast in the third row, and all jumps correspond to light changes by switching the lights on and off during the sequence.

4. Conclusion

We present an illumination-robust direct visual odometry algorithm for the autonomous flight of the aerial robot in a light-changing environment. The gain in robustness to irregular illumination changes is due to the fact that the affine illumination model is employed in each image patch and integrated in the direct motion estimation. The proposed VO algorithm estimates the 6-DoF camera motion accurately, and enables the aerial robot to fly autonomously and robustly under changing lighting conditions, which challenge to existing VO methods.