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学 位 論 文 題 目	Visual Localization for a Hopping Rover on an Asteroid Surface
論 文 審 査 委 員	主　　査　　准教授　川勝　康弘 准教授　坂井　真一郎 准教授　吉光　徹雄 教授　中谷　一郎　（愛知工科大学） 教授　倉爪　亮　（九州大学） 教授　久保田　孝 （JAXA 宇宙科学研究所）

論文内容の要旨

In future missions to asteroids, hopping rovers will likely be the vehicle of choice for surface exploration. In order for a mobile robot to explore on the remote surface of an asteroid, a critical capability is autonomous navigation, for which relative localization is an essential element. This thesis investigates the use of computer vision for performing relative localization on a hopping rover.

While there has been extensive research in visual localization for wheeled rovers, the conditions for visual perception on a hopping rover are quite different. First, a limited stereo baseline and a large distance between a rover and the ground during a hop lead to very poor stereo depth resolution. Also, without attitude control mechanisms, a hopping rover will undergo continuous rotational motion throughout a hop. Due to these conditions, this thesis proposes the use of a system of multiple monocular cameras pointing in diverging directions to perform visual localization on a hopping rover.

Although localization and mapping are two intricately related problems for a mobile robot, due to the limited computing resources on a hopping rover, this thesis will concentrate only on estimating the motion of a hopping rover over small intervals and concatenating the results, instead of building a large map of the environment that can be used to improve localization over the long term. In particular, this thesis will focus on visual odometry, which tracks features across an image sequence to recover the motion of a mobile robot. Two solutions for hopping visual odometry using a system of multiple cameras are proposed.

In the first solution for hopping visual odometry, the multiple cameras are used sequentially to perform monocular visual odometry. By using a single pair of stereo cameras at the beginning of a hop – when the stereo depth resolution is accurate – the absolute scale of the hopping motion is recovered. It will be shown that, even without overlap in the field-of-views between the cameras, by having a small overlap in time between the image sequences obtained from the multiple cameras, the motion across the multiple image sequences can be combined to reconstruct a single continuous hopping trajectory.

However, as will be seen from simulation results, there are several shortcomings to the first solution. First, in using the multiple cameras sequentially, if the ground terrain is observable by more than one camera, a selection needs to be made between the available cameras. As will be seen, this selection should be based on both the orientation of the camera with respect to the ground terrain, as well as the distance between the rover and the ground terrain. Second, in monocular visual odometry, errors are inevitably propagated from each relative motion estimate to the next. The continuous rotational motion of a hopping rover exacerbates the problem because observed features can be tracked only over a short time interval before they move out of view. As a result, errors accumulate quickly, leading to deteriorating performance over a long trajectory.

In the second solution for hopping visual odometry, the multiple cameras are used simultaneously to perform visual odometry. First, it will be shown that the pose estimation problem can be easily reformulated for a multiple cameras system. This allows tracked features from multiple cameras to be used together to solve for a single rover motion. Then, it will be shown that by combining the relative pose estimates from two rigidly-connected cameras without overlapping

views, the absolute scale factor can be recovered. This eliminates the need for stereo cameras, while retaining the ability to estimate motion with absolute scale. Thus, we refer to such a camera configuration as "***divergent stereo***".

Furthermore, the generalized epipolar constraint will be derived, from which a minimal solution for estimating the relative pose with absolute scale can be obtained. The solution applies to the special case of using 5 features from one camera and 1 feature from another, so it is referred to as the "***5+1-point***" algorithm. A sensitivity analysis of this solution to noise in the input data will be provided. Also, it will be shown that by using this method, because the scale factor can be independently estimated throughout a hop, the performance over a long traverse can be improved.

博士論文の審査結果の要旨

The review committee evaluated the thesis submitted by Edmond Wai Yan So and has concluded that it deserves to be a doctoral thesis.

The main contributions are summarized in the following two points..

- The transformation matrix of a rover relative to the initial position is estimated by the multiplication of the successive transformation matrices calculated using the tracked features in the camera images obtained during the movement of the spinning rover.

  The scale factor of the transformation matrix is inherited to the next one even when the used camera loses a sight on the terrain and the another camera is used.

  The proposal is unique and new in the point that the scale can be propagated without an overlapping view among the cameras, which has enabled the vision-based localization for a strongly limited resource of the asteroid rover.

- In order to reset the accumulated error of the scale caused by the multiplication of the transformation matrices, a fast scale recovery method has been proposed, which can be conducted at any time in the case that two cameras simultaneously track the terrain features in two time frames. The proposed method lightens the computer processing load for the practical use because the number of used features on the estimation is drastically reduced.

The PhD defense of Edmond Wai Yan So consists of one-hour open hearing on his research, followed by a closed discussion among the reviewers and himself. His answers to the questions raised by the reviewers were satisfactory.

On the presentation provided in the open hearing, he showed the capability which a doctor has to have in the point that he made the audiences understand the philosophy he brought to the world, only with some technical background, without the detailed knowledge.

The contributions to the thesis were condensed into one journal paper, two international conference papers with a review, and five domestic and international conferences and workshops. The journal paper will be published in 2011.

The review committee members all agreed that Edmond Wai Yan So deserves a PhD degree in engineering.