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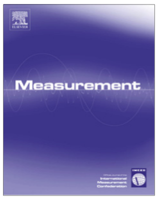

Uncertainty comparison of three visual odometry systems in different operative conditions

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ABSTRACT

An experimental comparison among visual odometry systems using lenses with three different focal lengths (an ultra wide angle, a medium wide angle and a telephoto lens) is presented. For each focal length, several translational and rotational tests are performed, taking into account and analyzing different positions of the system inside the laboratory. The influence of several operative parameters is analyzed, highlighting their effect on the visual odometry systems equipped with different lenses. Experimental errors and uncertainties obtained by the three systems are compared.

1. Introduction

The use of a vision system to perform an indirect measurement of the position and attitude of a vehicle is well known, e.g. see [1–12], but it is a still-open research subject, as proved by many recent papers, e.g. see [13–16]. A vision system for motion measurement is particularly useful for planetary space exploration, when a satellite global positioning system is not available and other traditional measurement systems, such as inertial sensors or optical encoders mounted on the vehicle wheels, are affected by wide drifts. When the motion estimation takes place incrementally without a prior knowledge or a simultaneous evaluation of a global map of the environment, the vision estimation method is called Visual Odometry (VO). An interesting overview and an introducing tutorial on VO can be found in [11,12]. In VO, the displacement and rotation of a stereo vision system are measured through the images taken by the two cameras. A stereo triangulation method yields the three dimensional (3D) position of the observed landmarks in the environment. If the same landmarks fall within the Field of View (FOV) of the cameras in two subsequent positions, the two 3D point clouds observed in the two positions are used to evaluate the stereo camera movement. The whole trajectory is then calculated combining each motion step.

Ref. [5] summarizes some of the most important findings in VO yielded by the Mars Exploration Rovers Spirit and Opportunity of NASA. Ref. [6], for the first time, analyzes the need of an anisotropic uncertainty modeling for 3D acquired landmarks. Ref. [9] describes an implementation of the Heteroscedastic Error-In-Variables estimator, modified to reduce the bias error that arises during VO.

In the present work the attention is focused on comparing the measurement uncertainties obtained by a visual odometry system using lenses with different focal lengths. The main purpose is to experimentally compare the metrological behavior obtained with different lenses, and not to find the best position measurement method based on a vision system. Thus, other approaches that try to reduce the measurement error using or building a map of the environment, such as Simultaneous Localization and Mapping, are not analyzed.

The main aim of the present comparison among different focal lengths and, thus, different values of Field of View

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(FOV) is to yield useful advices to the problem of lens selection for the stereo camera of a visual odometry system. Ref. [4] performed numerical simulations to evaluate which FOV yields the smallest long-range error of a visual odometry system. Authors analyzed several values of FOV between 15° and 90° using a numerical simulation procedure, and found that the optimal FOV is approximately 35°. In [4], the obtained numerical results are not validated by an experimental comparison. Despite the optimal values of FOV found in [4], Ref. [5] says that their VO algorithm has been experimentally tested using the Jet Propulsion Laboratory's Rocky 8 rover, whose cameras have a horizontal FOV equal to 80° and 64° along vertical direction. Other tests were run on the MER Surface System Testbed Lite rover with a 120° FOV cameras and, of course, on the Mars rovers with a 45° FOV. However, in [5] there is not a rigorous comparison among experimental results obtained with these different FOV values. Moreover, different values of FOV are associated with different cameras and different rovers, thus, a direct comparison could not be meaningful, since FOV is not the only parameter that changes from one case to another one. Our contribution is a direct experimental comparison among visual odometry systems with three different focal lengths and FOV (an ultra wide angle, a medium wide angle and a telephoto lens), performed with all other influencing parameters kept constant (same cameras, same relative positions of cameras, same elevation angle of cameras, same imposed rotary and linear motions) and with a rigorous uncertainty analysis according to [17,18].

In [28], we applied about the same VO algorithm described in the present manuscript to the measurement of a vehicle trajectory. The vehicle was driven along a closed path and was brought to a final position nominally equal to the initial one; the uncertainty of both the initial and final position measurements was about 1 cm. The on-board mounted stereo camera acquired two video sequences with fixed frame rate during the motion. The optical encoders mounted on the wheels were not able to acquire the trajectory with an uncertainty one order of magnitude better than the VO system. Thus, only the final position could be used to analyze the errors and the uncertainty achieved by the VO system. In [29], the same authors described the behavior of different VO systems using a complete new laboratory set-up, which allows to analyze the errors and uncertainties obtained by each VO system for all the acquired motion steps and not only at the end of the motion, as in [28]. The experimental set-up described in [29] allows to measure both linear displacements and rotations imposed to the stereo camera during all the motion steps with an uncertainty an order of magnitude better than that of the VO system. However, in [29], the experimental set-up, which is employed to move and to measure the imposed rotations and translations, is positioned in only one fixed location inside the laboratory. In the present manuscript, we used the same experimental set-up and the same method described in [29], but we add several experimental tests changing the location of the experimental set-up inside our laboratory. Moreover, during the rotation test in [29], only clockwise (CW) rotations (0–90°) are considered. In the present manuscript, for all the new locations of the set-up, both CW and counterclockwise (CCW) rotations ($0\ldots90°$; $0\ldots-90°$) are taken into account. Since the obtained results are greatly influenced by the scene observed by the stereo camera, the added new tests in different locations and using 180° rotations allow to obtain more general conclusions.

Another new contribution of the present manuscript is a more detailed analysis of the results, trying to identify possible parameters that influence the behavior of the VO system, e.g. the mean distance and the spatial distribution of the observed 3D landmarks, or their number.

Ref. [30] describes a method similar to the one employed in this manuscript. However, in [30] only a telephoto lens is taken into account and, thus, the achieved results can not directly be applied to other lenses, particularly to a wide angle lens. Another important difference between [30] and the present manuscript is that the latter analyses a whole trajectory obtained composing several motion steps, while in [30] only a single motion step is taken into account both for displacements and rotations. The total travels (100 mm for longitudinal displacement, 70 mm for transverse displacement, 3° for rotation) discussed in [30] are very small, since they correspond to only one motion step. The purpose of that work was to study the effect of the motion step amplitude (only with a telephoto lens aimed at a rather near scene).

In Section 2, the paper describes a measurement method broadly based on the NASA rovers approach [4,5] and slightly updated combining together subroutines and procedures more recent and advanced. Section 3 presents the performed uncertainty analysis, and Section 4 discusses the experimental set-up and the obtained results.

2. Measurement algorithm

The measurement approach is very similar to that described in previous papers [28–30]. Thus, in this section the main phases of the method are only outlined. In each motion step, the goal is to evaluate the displacement and rotation of a calibrated stereo camera through the analysis of the images acquired in two subsequent positions. The whole trajectory is then evaluated combining each single motion step.

The first phase is to calibrate the stereo camera as described in [27], to evaluate the intrinsic and extrinsic parameters of a stereo system. After optical calibration, a detector algorithm can be used to find out the 2D features (keypoints) which are the projections of physical landmarks in the two images. Then, the 2D region around each detected feature is described by a descriptor algorithm. For each 2D feature, a suitable distance, defined using the descriptor, is employed to find the nearest one in different images. Corresponding 2D features should be the projections of the same 3D landmark in different images. In literature are known several feature detectors and descriptors, see [19–26]. Particularly, see [23], the Hessian–Affine detector and the Maximally Stable Extremal Regions (MSER) approach are a good choice to find features even in presence of relatively wide scale and/or rotation