UNIVERSIDAD DE COSTA RICA

IPCV-LAB Image Processing and Computer Vision Research Laboratory

Field Tests on Flat Ground of an Intensity-Difference Based Monocular Visual Odometry Algorithm for Planetary Rovers

Geovanni Martinez

School of Electrical Engineering, Dept. of Electronic and Telecommunications

geovanni.martinez@ucr.ac.cr

IPCV-LAB robot VISION

Abstract

In this contribution, the experimental results of testing a monocular visual odometry algorithm in a real rover platform over flat terrain for localization in outdoor sunlit conditions are presented. The algorithm computes the three-dimensional (3D) position of the rover by integrating its motion over time. The motion is directly estimated by maximizing a likelihood function that is the natural logarithm of the conditional probability of intensity differences measured at different observation points between consecutive images. It does not require as an intermediate step to determine the optical flow or establish correspondences. The images are captured by a monocular video camera that has been mounted on the rover looking to one side tilted downwards to the planet's surface. Most of the experiments were conducted under severe global illumination changes. Comparisons with ground truth data have shown an average absolute position error of 0.9% of distance traveled with an average processing time per image of 0.06 seconds.

Intensity-Difference Based Monocular Visual Odometry Algorithm

- **Alternative algorithm:** It was proposed in [1] as an alternative **to the long-established feature based stereo visual odometry algorithms** [2, 3, 4, 5].
- **Positioning computation:** The rover's 3D position is computed **by integrating the frame to frame rover's 3D motion $\Delta\mathbf{B}$ over time**.
- **Type of sensor:** The frames are taken by a **single video camera rigidly attached to the rover** (see Fig. 1 and Fig. 2.a).
- **Direct motion estimation:** **The frame to frame rover's 3D motion $\Delta\mathbf{B}$ is directly estimated by** maximizing the likelihood function of intensity differences at the N key observation points, without establishing correspondences between features or solving the optical flow as an intermediate step, just directly **evaluating the frame to frame intensity differences measured at the N key observation points**. The key observation points are image points with high linear intensity gradients.
- **Compact solution:** The resulted frame to frame rover's 3D motion estimates have the following compact form:

$$\Delta\mathbf{B} = \left(\mathbf{O}^\top\mathbf{O}\right)^{-1}\mathbf{O}^\top\mathbf{FD} \quad (1)$$

  where $\mathbf{O}$ is the observation matrix and $\mathbf{FD}$ is a vector with the intensity differences measured at the N observation points.
- **Iterative algorithm:** Since the observation matrix $\mathbf{O}$ resulted from several truncated Taylor series expansions (i.e. approximations), the Eq. (1) needs to be applied iteratively to improve the reliability and accuracy of the estimation.

Problem Statement

- **Field tests missing:** Despite that in [1] the above intensity-difference based monocular visual odometry algorithm has been extensively tested with synthetic data, an experimental validation of the algorithm in a real rover platform **in outdoor sunlit conditions** is still missing.

Main Contribution

- **To provide first field test results:** This paper's main contribution is to provide the results of the first outdoor experiments towards validation of the algorithm, which was obtained for now **on surfaces of little geometrical complexity such as flat ground**, to help to clarify whether the algorithm really does what is intended to do in real outdoors situations **under severe global illumination changes**.

Results

The intensity-difference based monocular visual odometry algorithm has been implemented in the programing language C and tested in a Clearpath Robotics™ Husky A200™ rover platform (see Fig. 1). In total 343 experiments were carried out over flat paver sidewalks only, under severe global illumination changes due to cumulus clouds passing fast across the sun. Special care was taken to avoid the rover's own shadow in the scene. During each experiment, **the rover is commanded to drive on a predefined path at a constant velocity of 3 cm/sec over a paver sidewalk, usually a straight segment from 1 to 12 m in length or a clockwise arc from 45 to 280 degrees with 2.5 m radius**, while a single camera with a real time image acquisition system captures images at 15 fps and stores them in the onboard computer. The camera has an image resolution of 640x480 $pixel^2$ and a horizontal field of view of 43 degrees. It is located at 77 cm above the ground looking to the left side of the rover tilted downwards 37 degrees (see Fig. 1 and Fig. 2.a).

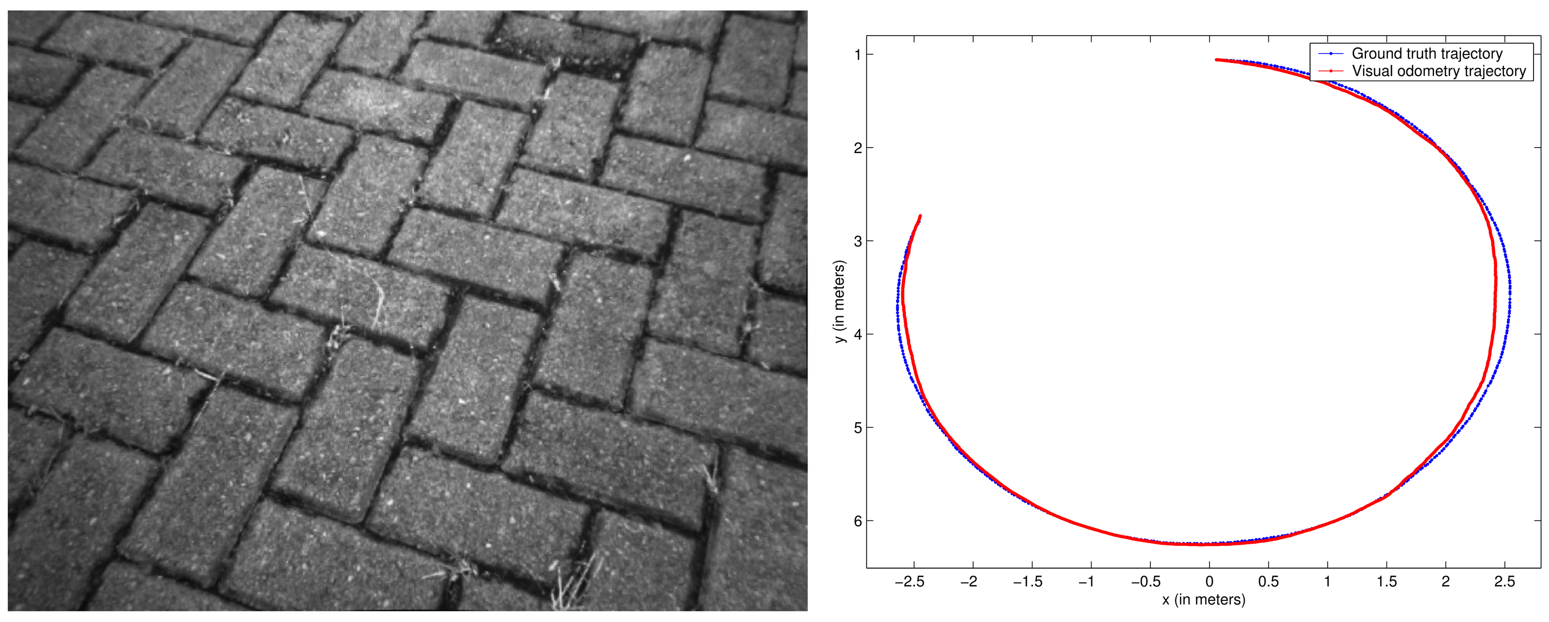
	mean	standard deviation	min	max
Observation points per image	15906	67.74	15775	15999
Iterations per image	14.88	1.89	12.33	19.09
Processing time (in seconds) per image	0.06	0.006	0.05	0.08
Absolute position error	0.9%	0.45%	0.31%	2.12%

Table 1: Summary of experimental results.

Simultaneously, a Trimble® S3 robotic total station (robotic theodolite with a laser range sensor) tracks a prism rigidly attached to the rover and measures its 3D position with high precision ($\leq$ 5 mm) every second. After that, the intensity-difference based monocular visual odometry algorithm is applied to the captured image sequence. Then, the prism trajectory is computed from the rover's estimated 3D motion. Finally, it is compared with the ground truth prism trajectory delivered by the robotic total station.

All the experiments were performed on an Intel® Core™ i5 at 3.1 GHz with 12.0 GB RAM. **In Table 1, the main experimental results are summarized.** The tracking was not lost in any of the experiments. As an example, Fig. 2.b depicts the visual odometry trajectory and the robotic total station trajectory for the path number 334 forming an arc segment of the 343 different paths driven by the rover during the experiments.

Figure 1: Clearpath Robotics™ Husky A200™ rover platform and Trimble® S3 robotic total station used for experimental validation.



(a) (b)

Figure 2: (a) Example of an image with resolution 640x480 $pixel^2$ captured during experiment number 334. The camera is located at 77 cm above the ground looking to the left side of the rover tilted downwards 37 degrees. (b) Trajectory obtained by visual odometry (in red) and corresponding ground truth trajectory (in blue) for the experiment number 334. In the experiment the rover was commanded to drive a clockwise arc of 280 degrees with radius of 2.5 m over paver sidewalk.

Conclusions

- **Processing time per image and accuracy so far:** After testing the monocular visual odometry algorithm proposed in [1] in a real rover platform for localization in outdoor sunlit conditions, even under severe global illumination changes, over flat terrain, along straight lines and gentle arcs at a constant velocity, without the presence of shadows, and comparing the results with the corresponding ground truth data, we concluded that the algorithm is able to deliver the rover's position in average of **0.06 seconds** after an image has been captured and with an average absolute position error of **0.9% of distance traveled**.
- **So far so good:** Although the experiments so far have been only on flat ground, these results closely resembles those achieved by known traditional feature based stereo visual odometry algorithms, whose absolute position errors of distance traveled are **within the range of 0.15% and 2.5%** [2, 3, 4, 5].

Forthcoming field tests

- **Field tests on rough terrain:** In the future, the algorithm will be tested over different types of terrain and geometries, and also it will be made robust to shadows.

References

[1] G. Martinez, "Intensity-Difference Based Monocular Visual Odometry for Planetary Rovers" in *New Development in Robot Vision*, vol. 23 of the series Cognitive Systems Monographs, Berlin, Heidelberg: Springer Verlag, 2014, ch. 10, pp. 181–198.

[2] A. Howard, "Real-time Stereo Visual Odometry for Autonomous Ground Vehicles", in *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, Nice, France, 2008 Sept. 22-26, pp. 3946–3952.

[3] M. Maimone, Y. Cheng, L. Matthies, "Two Years of Visual Odometry on the Mars Exploration Rovers", *J. of Field Robotics*, vol. 24, no. 3, pp. 169–186, Mar. 2007.

[4] D. Nister, O. Naroditsky, J. Bergen, "Visual Odometry for Ground Vehicle Applications", *J. of Field Robotics*, vol. 23, no. 1, pp. 3–20, Jan. 2006.

[5] P. Corke, D. Strelow, S. Singh, "Omnidirectional Visual Odometry for a Planetary Rover", in *IEEE Int. Conf. on Intelligent Robots and Systems*, Sendai, Japan, 2004 28 Sept.-2 Oct., pp. 4007–4012.

Acknowledgements

This work was supported by the University of Costa Rica. Thanks to Reg Willson from the NASA Jet Propulsion Laboratory for kindly delivering the implementation of Tsai's coplanar calibration algorithm, which was used in the experiments. Thanks also to Esteban Mora for helping transport the equipment to and from the test locations and for helping collect the data.

Prof. Dr.-Ing. Geovanni Martínez
Phone: +506 2 511 2631
Email: geovanni.martinez@ucr.ac.cr
WWW: http://ipcv-lab.eie.ucr.ac.cr

UCR UNIVERSIDAD DE COSTA RICA

www.ucr.ac.cr

IAPR MVA-2017, May 8-12, 2017, Nagoya, Japan