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Error analysis of satellite attitude determination using a vision-based approach

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ABSTRACT

Improvements in communication and processing technologies have opened the doors to exploit on-board cameras to compute objects' spatial attitude using only the visual information from sequences of remote sensed images. The strategies and the algorithmic approach used to extract such information affect the estimation accuracy of the three-axis orientation of the object.

This work presents a method for analyzing the most relevant error sources, including numerical ones, possible drift effects and their influence on the overall accuracy, referring to vision-based approaches. The method in particular focuses on the analysis of the image registration algorithm, carried out through on-purpose simulations. The overall accuracy has been assessed on a challenging case study, for which accuracy represents the fundamental requirement. In particular, attitude determination has been analyzed for small satellites, by comparing theoretical findings to metric results from simulations on realistic ground-truth data. Significant laboratory experiments, using a numerical control unit, have further confirmed the outcome.

We believe that our analysis approach, as well as our findings in terms of error characterization, can be useful at proof-of-concept design and planning levels, since they emphasize the main sources of error for visual based approaches employed for satellite attitude estimation. Nevertheless, the approach we present is also of general interest for all the affine applicative domains which require an accurate estimation of three-dimensional orientation parameters (i.e., robotics, airborne stabilization).

1. Introduction

The estimation of the three-axial orientation of a moving object represents a complex and challenging task, with impact in diverse applicative domains (marine, aerospace, biomedical, etc.). These estimates are usually employed for the automatic guidance and control of different kinds of devices, for instance for device stabilization, or to perform target actions, as for robotic industrial applications requiring the knowledge of the robot pose parameters to accomplish a specific task. The orientation angles (also known as "attitude" in satellite guidance, Hall, 2003) can be estimated from systems integral with the device to be monitored, according to an *ego-motion approach*, or from external systems, integral with the world reference frame, according to an *object tracking* approach. Accordingly, measuring systems can be either mounted *on board* (i.e., according to the *direct sensor orientation* approach, Schwarz et al., 1993), or external to the device whose orientation has to be measured. In the first case, usually ensembles of different sensors are *embedded* in the device – typically Inertial Navigation Systems (INS) and GPS (Global Positioning System) – and a subsequent data integration is required in order to achieve the orientation measures. In the second case, reference patterns or fiducial (either natural or artificial) markers, integral with the target object, are *sensed* from off-board devices and registered in the world reference frame.

In this context, applications of computer vision technologies are nowadays standing out for the advantages they can provide. As an example, navigation systems based on *visual odometry* (Nister et al., 2006) have been conceived to achieve measurements of the motion parameters of the controlled object. This problem has been commonly addressed using ego-motion estimation, where the camera's pose in an inertial reference frame is recovered by processing images of the surrounding environment acquired from one or more cameras mounted on board. In aerial mapping applications, Aerial Triangulation (AT) has represented the main indirect determination method for estimating exterior orientation

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parameters by processing blocks of images with a known pattern of ground control points. Integration of AT with INS/GPS represents the current dominant trend for such applications, according to the *integrated sensor orientation* paradigm (Ip et al., 2007). In the robotic field, *visual servoing* applications (Choi et al., 2008) are acquiring importance, usually taking advantage of stereo vision to recover three-dimensional pose parameters.

Current vision-based approaches have focused their attention on the *robustness* issue, rather than on the accuracy performance, due to the large amount of data gathered from a vision-based sensor. However, in applications for which accuracy constitutes the fundamental requirement, an in-depth analysis of error sources and their dynamics represents a crucial step to reach the desired performance (both in static and dynamic conditions) and can limit potential undesired effects, like error drift. In this work, we present a methodological approach for assessing accuracy performance in a videogrammetric framework aiming to estimate the three-dimensional orientation from remote sensed image sequences. It is structured into general fundamental stages, that make it suitable for similar applicative domains sharing the same constraints (i.e., robotics, airborne guidance, etc.). Through the identification of the main different sources of error, our methodological approach aims at evaluating how they can affect the resulting overall accuracy. Briefly, it can be summarized according to three main stages:

- **analysis of our vision based-approach**: the relations between the geometric transforms in the image domain and the object orientation parameters in the three-dimensional spatial domain stemming from our framework are presented, in order to characterize the environment and the sensor *models*;
- **error sources identification**: error contributions are identified at different levels, moving from theoretical models toward the image registration method employed;
- **design of an experimental framework**: on-purpose simulation configurations are designed to identify the "weight" of each error component on the overall performance. Experiments are used to reject or confirm the hypotheses formulated in the simulation framework regarding different error contributions.

As a case study, we address a mission critical application, that is the estimation of the three-axial attitude parameters of a Low Earth Orbit (LEO) small satellite, by exploiting the vision-based approach we conceived for autonomous guidance purposes and proposed in Bevilacqua et al. (2009a), Bevilacqua et al. (2009b), Bevilacqua et al. (2009c), Bevilacqua et al. (2010a). This approach exploits visual information only, the camera integral with the satellite acquiring terrestrial images to estimate satellite orientation using image registration. Based on a visual features tracking algorithm, the attitude parameters are recovered from the geometrical transformation that maps views of the Earth acquired at different epochs along the orbit. In this applicative case, where high accuracy constitutes the most compelling requirement for proper aircraft stabilization, the methodological approach used for error analysis turns out to be crucial.

This work is organized as follows. Section 2 describes the methods employed in literature to estimate attitude parameters and to assess their accuracy. The novelty of our method and the advantages brought are then discussed in Section 3. General considerations about the geometrical relations in different domains (image and spatial) are also provided in this section. In Section 4 our image registration algorithm is discussed and compared to other approaches. In Section 5 an in-depth error analysis is carried out to describe the influence of different sources of error. The framework designed for simulations of realistic orbits on *real sampled* satellite images is illustrated in Section 6. Section 7 reports the results regarding these simulations and experiments related to images by using a laboratory testbed. The discussion of the results in Section 7 introduces to the future perspectives summarized in Section 8.

2. Previous works

Estimation of three-dimensional orientation parameters of a rigid body, both in static and dynamic conditions, has been generally faced by researchers by using specific devices and sensors, depending on the applicative field. In fact, the choice of measurement technologies and methodologies is usually driven by the applicative requirements in terms of cost, setup complexity, robustness to environmental and operating conditions and accuracy performance. According to a simplified overview, the approaches adopted by most of the currently available systems can be summarized into two main categories.

According to the first category, a combination of electromechanical sensors is employed. Advances in Micro-Electro-Mechanical Systems (MEMS) and Fiber-Optic Gyros (FOGs) (Lefevre et al., 2011) technologies have contributed to the wide employment of INS/GPS integrated sensors as a trade off among flexibility, cheapness and accuracy. Often, Inertial Measurement Units (IMU) integrate information coming from different sensors (e.g., three axial linear accelerometers, angular rate gyroscopes) and magnetometers to estimate the three-dimensional pose of the object on which they are mounted. They are employed in mapping and guidance (Wendel et al., 2006) applications, providing high data rate but requiring on-purpose calibration procedures and data filtering algorithms, being prone to dead reckoning drift effects. Accuracy performance of such systems have been characterized with numerical simulations and field experiments and are shown to be in the order of degrees (Wendel et al., 2006). As for satellite missions, where estimation accuracy is a key requirement, orbital gyrocompass and horizon sensors have been also utilized to estimate attitude angles. In Low Earth Orbit (LEO) systems, infrared radiation deflected by the atmosphere can lead to false detections, that worsen accuracy as low as few degrees (Pisacane and Moore, 2005). These sensor sets are generally calibrated and rigged up together, each of them potentially contributing to the overall system accuracy. Also, high performance navigation-grade (0.01 deg/h and 25 μg) Ring Laser Gyro (RLG) and FOG IMU are successfully employed for aircraft navigation. However RLGs, in spite of their reliability, still could suffer from some drawbacks such as the need for perfect sealing of the gas enclosure (Lefevre et al., 2011). On the other side, even FOGs can achieve extremely high performance, making them suitable for applications such as precise aiming of telescopes and imaging systems. However, the accuracy of the system is strictly related to the accuracy of the calibration step needed to define which indication corresponds to zero angular velocity.

The second approach relies on vision-based methods. *Optical Flow* estimation from image sequences is generally integrated with INS/GPS platforms in a multi-sensor approach to compensate for dead reckoning drifts in Unmanned Aerial Vehicles (UAV, Ding et al., 2009) and spacecraft navigation (e.g., Inertial Stellar Compass (Brady et al., 2002)). Recently, Simultaneous Localization and Mapping (SLAM) approaches have been applied jointly with visual odometry in general environments to curb dead reckoning effects for long *looping-path* image sequences (i.e., so that the same scene is revisited at the end of the sequence). The work in Caballero et al. (2009) well summarizes the state of the art in this context. However, these approaches aim mostly at guaranteeing robustness in looping path sequences, while accuracy is left in the background, since it does not represent a key issue for these applications. Accordingly, the error analysis is not carried out in depth in order to increase the accuracy.