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Parametric study of sensor placement for vision-based relative navigation system of multiple spacecraft

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ABSTRACT

In order to overcome the limited range of GPS-based techniques, vision-based relative navigation methods have recently emerged as alternative approaches for a high Earth orbit (HEO) or deep space missions. Therefore, various vision-based relative navigation systems use for proximity operations between two spacecraft. For the implementation of these systems, a sensor placement problem can occur on the exterior of spacecraft due to its limited space. To deal with the sensor placement, this paper proposes a novel methodology for a vision-based relative navigation based on multiple position sensitive diode (PSD) sensors and multiple infrared beacon modules. For the proposed method, an iterated parametric study is used based on the farthest point optimization (FPO) and a constrained extended Kalman filter (CEKF). Each algorithm is applied to set the location of the sensors and to estimate relative positions and attitudes according to each combination by the PSDs and beacons. After that, scores for the sensor placement are calculated with respect to parameters: the number of the PSDs, number of the beacons, and accuracy of relative estimates. Then, the best scoring candidate is determined for the sensor placement. Moreover, the results of the iterated estimation show that the accuracy improves dramatically, as the number of the PSDs increases from one to three.

1. Introduction

Multiple spacecraft have attracted increasing research attention due to their reconfiguration ability. For these advantages, a construction mission was proposed for a large system by connecting small satellites [1]. Also, the operation of the multi-spacecraft was used to maintain and service to space stations such as International Space Station (ISS) [2] and Tiangong [3]. The European Space Agency (ESA) studied an active debris removal (ADR) by multiple cube-satellites [4]. Therefore relative navigation techniques, to estimate the position and attitude information between each spacecraft, have been becoming indispensable in recent years since those missions require highly accurate proximity operations in the space environment.

A global positioning system (GPS) based approaches have been widely used for the relative navigation of the multiple spacecraft owing to accuracy, robustness and cost efficiency [5]. A carrier phase differential GPS (CDGPS) was proposed and demonstrated by ground experiments that showed accurate results for relative information [6]. The CDGPS was also validated by using flight data from a gravity recovery and climate experiment (GRACE) mission [7]. The Automated Transfer Vehicle (ATV), funded by the ESA, was used for the rendezvous mission to service the ISS [8]. In order to estimate relative information for the ATV, a relative GPS and Videometer were applied for the far and close rendezvous phases respectively. Moreover, a decimeter level real-time onboard algorithm, based on a dual-frequency CDGPS, was investigated in a low Earth orbit (LEO) for a long baseline application: on the order of hundreds of kilometers [9]. The GPS-based approaches have gradually improved the accuracy of the relative information. The coverage of the GPS is, however, around 1,500 km from the surface of the Earth, which can only be used in the LEO [10].

In order to overcome the limited range of the GPS-based techniques, vision-based relative navigation methods have emerged as alternative approaches for a high Earth orbit (HEO) or deep space missions. A vision-based system using a camera was proposed to track a standard rhombus mark mounted on other spacecraft in the vicinity [11]. Then position and attitude estimates were obtained using feedback control loops for the docking mission. Also, a single monochrome camera was applied for a relative state estimator [12]. This approach dealt with an exterior orientation problem using a globally convergent nonlinear iterative algorithm based on an iterative photogrammetric estimation and multiplicative extended Kalman filter (MEKF). In [13], a gray-scale camera was used to implement a pose estimation algorithm with a ranging

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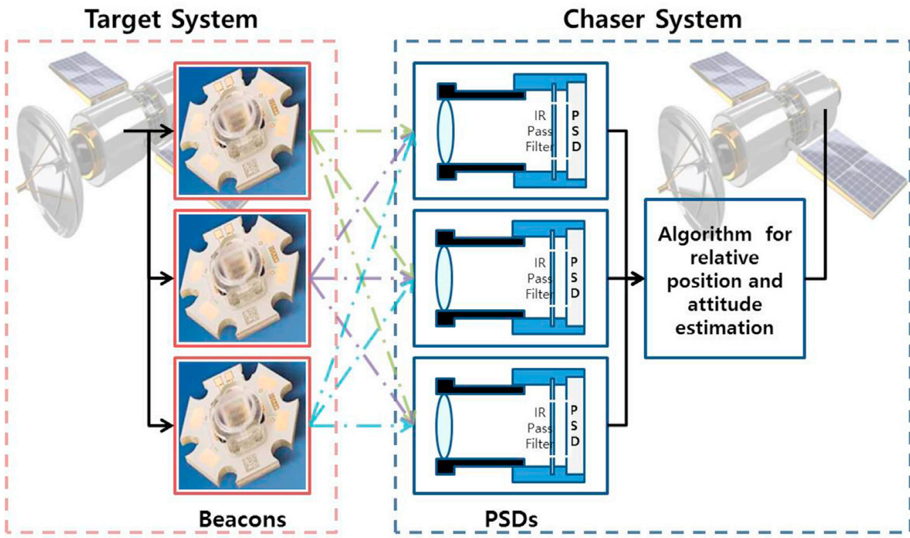

Fig. 1. Vision-based relative navigation system.

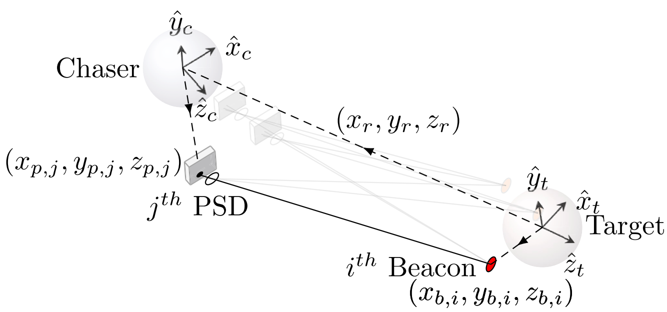

Fig. 2. Coordinate system of the relative navigation.

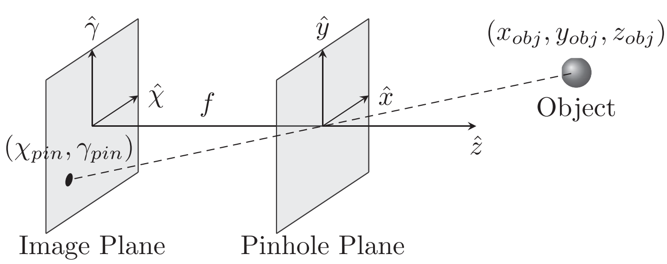

Fig. 3. Pinhole camera model.

sensor. Instead of using the camera, a position sensitive diode (PSD) sensor with light sources, as called as beacons, was developed as a vision-based navigation system (VISNAV) [14]. The VISNAV has outstanding advantages as follows: it is affordable for small-sized spacecraft due to using small sensor; has wide field-of-view (FOV), and consumes less computational power than the camera. An extended Kalman filter (EKF) was applied using the VISNAV with gyro data to determine not only relative navigation data but also gyro biases between two spacecraft [15]. In [16], a coupled relative dynamics was derived for the formation flight of two satellites. And an EKF is applied based on the line-of-sight (LOS) observations of the PSD without gyro information. An unscented Kalman filter method (UKF) is also applied for the PSD-based navigation system. A modified UKF to add control inputs was designed for an inner-formation gravity measurement satellite system (IFGMSS) [17]. A sigma-point unscented predictive filter (UPF) was proposed in satellite formation by including the effect of J2 [18].

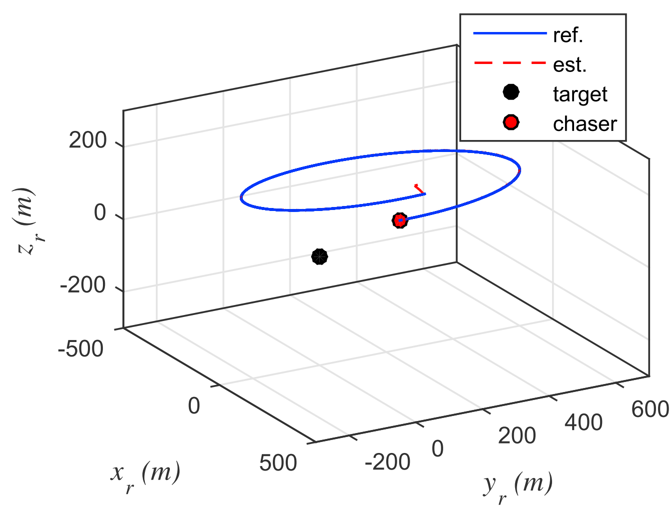

Fig. 4. Position trajectory.

A sensor placement problem involves the implementation of the vision-based navigation system on the exterior of spacecraft due to its limited space for the sensors or beacons. Moreover, the number and location of the sensors are deeply related to the accuracy of the relative navigation algorithm. In the space applications, most of the sensor placement dealt with a structural health monitoring for large space structures (LSS) [19,20,21]. There are only a few cases for the placement methods of directional sensors. The locations of sun sensors were optimized using a hybrid genetic algorithm and annealing to minimize the required number of the sensors with respect to coverage [22]. In order to design sun sensor arrays, an optimization method was proposed with two cost functions which are to minimize bias and variance errors. The optimal sensor placement was verified via cases studies regarding the changes of weighting values [23].

There are various studies for a camera placement problem in ground applications. An optimal camera placement was researched to minimize the number of cameras covering a particular area and the total cost of the sensors with different characteristics [24]. Also, an optimal camera placement was proposed for three-dimensional motion capture systems to improve triangulation accuracy in the presence of dynamic occlusion [25]. However, the sensor placement problem of the vision-based navigation system for the space applications has not been thoroughly