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GNSS Guided Relative Positioning and Attitude Determination for Missions with Multiple Spacecrafts

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Introduction

GNSS-guided relative positioning techniques can be applied to a number of missions with multiple spacecrafts as for example formation flight, constellation control and rendezvous between spacecrafts.

Currently there is a trend in space mission design towards payload distribution. For strategic, economic and operational reasons, one satellite, integrally carrying all payload, is replaced by a cluster or swarm of smaller satellites. The function of the former integrated satellite is distributed over the elements of the cluster. Major applications areas will be telecommunication and Earth observation. Depending of the level of coordination between the satellites of a cluster we refer this kind of system as a formation flight or constellation control [1]. Multiple satellites belonging to the same mission where the payload is divided over more than one satellite are often referred to as distributed satellites.

Formation flying typically involves active, real-time, closed-loop control of multiple, cooperating satellites in autonomous formation. Thus, formation flying requires the direct control of one spacecraft relative to one or many other spacecraft.

Constellation control typically does not require this level of autonomy, real-time coordination, or consideration of the relative positions or orientations of multiple spacecraft - only that they maintain themselves within their own prespecified boxes without collision or changing for example overall coverage of the Earth.

The techniques required for formation flight and constellation control are similar to the techniques used in rendezvous between spacecrafts, where one spacecraft, typically referred to as the chaser, has to determine its relative position towards the target satellite while approaching this satellite. The rendezvous is normally followed by docking between the two spacecrafts.

Rendezvous, constellations control and formation flight rely critically on subsystems such as absolute and relative navigation, satellite cross-link communications and data transfer. The ability to determine and control the relative positions, orientations, and respective velocities for a vehicle or fleet of vehicles is only as effective as the sensors onboard these vehicles. In addition to relative and absolute positioning, GNSS can provide low-cost spacecraft timing systems and vehicle attitude determination.

Overview of Previous and Future GNSS Guided Relative Navigation Missions

In the US, Europe and Japan, a number of missions for relative navigation have been performed or are currently being developed.

The very first mission to use GNSS (GPS) signals for relative navigation in space was the Japanese ETS-7 mission. The ETS-7 mission, consisting of 2 sub-satellites called Chaser and Target, performed a number of rendezvous and docking experiments in 1997 and 1998. For this mission a communication link between the two spacecrafts was implemented, which broadcasted the GPS observation data from the Target to the Chaser spacecraft that made real-time relative navigation possible.

Other examples of orbital experiments are the SNAP-1 and Tsinghua-1 from SSTL, the DART mission which was the first real autonomous rendezvous and docking experiment, EO-1 and Landsat-7 experiment that marks a key milestone on the way to autonomous, multi-spacecraft, formation flying and missions planned for the near future as the ATV, and PRISMA project in Europe, and HTV in Japan. According to [2], there are currently more than 25 formation flight projects under consideration in the US

Examples of application satellites where precise relative navigation is a requirement for mission success are interferometric radar missions such as Terrasar-X and TanDEM-X, and cartwheel mission concepts that exploit two or more satellites to obtain a bistatic configuration required for geometric estimation of the earth's topography. The primary mission objective for this kind of missions requires the relative position to be known within a 2 mm precision (1-dimensional). [3]

Recent research at Delft University of Technology has proved, using orbital data from GRACE and CHAMP, that this kind of accuracy is achievable. A processing strategy that have been identified for relative spacecraft positioning using an extended Kalman filter/smoother has proven to work satisfactorily when tested with orbital GPS data. The EKF processes single difference GPS pseudorange and carrier phase observations and uses (pseudo) relative spacecraft dynamics to propagate the relative satellite state over the observation epochs. The EKF can resolve and incorporate the integer double difference carrier phase ambiguities, which is commonly regarded as the key to precise GPS based relative positioning. Estimation of the integer ambiguities is accomplished by the well known Least Squares Ambiguity Decorrelation Adjustment (LAMBDA) method [4]. When validating the GRACE relative position solutions from the EKF with reference observations, it has been shown that an actual overall relative position precision of 0.9 mm (1-dimensional) is achieved.

GNSS-based Attitude Determination

If the relative position (i.e. baseline) between 2 GNSS antennas is known, it is possible to determination the orientation of the baseline from the phase difference between the observations at the 2 antennas. This kind of technique was demonstrated very successfully onboard the SERVIS-1 satellite with a configuration of 2 baselines (i.e. 3 antennas) [5]. The recently achieved accuracy for relative navigation between disturbed satellites opens new possibilities for attitude determination for this kind of missions, which will be discussed in this paper.

Research on Formation Flight at DEOS, Delft University of Technology

At this moment GNSS guided formation flight is one of the keystone research topics of the DEOS group at the faculty of aerospace engineering, Delft University of Technology. Three Ph.D. students are working in parallel on this research. One person is looking into the implementation expects of the work described in [3]. The second person is analyzing the performance of different satellite formations and future sensor technology to map the time-varying gravity field of the Earth. The activities comprise investigations into the suitability and feasibility of various satellite formations, the propagation of errors into estimated gravity field parameters, time and frequency domain sensitivity studies, the separation between individual contributors to the time-varying gravity field and its relation with satellite mission parameters. For the third position the purpose is to demonstrate the capabilities of formation flying using GNSS for relative positioning between, and attitude determination of, the elements of a formation of satellites. The mathematical models for positioning and attitude determination based on the observed ranges will be developed. This implies adequately accounting for a wide range of error sources in the highly dynamic environment of flying objects, as well as capturing the noise characteristics in a stochastic model.

Summary

This paper will describe current trends in GNSS guided relative navigation between spacecrafts. It will describe previous missions and planned missions for the near future. It will explain the techniques used for relative navigation and will explore the possibilities to use GNSS-based attitude determination techniques for distributed satellites.

Literature

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