A NAVIGATION PROCESSOR FOR FLEXIBLE REAL-TIME FORMATION FLYING APPLICATIONS

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ABSTRACT – A powerful onboard navigation processor dedicated to the GPS-based guidance, navigation, and control of satellite formations in real-time has been built up. The system features an industrial Power PC 823e processor supporting multiple Global Positioning System (GPS) receiver interfaces and thus allows flexible hardware-in-the-loop simulations of complex satellites formations comprising more than two spacecraft. The real-time operating system BOSS separates the kernel runtime system and a hardware dependant layer of the navigation processor, which significantly speeds up software development and implementation on the hardware platform. The same processor type and the operating system have successfully been flown in space, onboard the BIRD small satellite. A Real-time Formation Flying software has been developed and implemented on the processor. It applies a complex dynamic model of the spacecraft motion to estimate the absolute as well as the relative spacecraft states, based on GPS pseudoranges and carrier phase measurements. Making use of a float integer ambiguity resolution of the GPS carrier phases, a hardware-in-the-loop relative position reconstruction at the range of some centimeters has been demonstrated. In addition, the navigation processor has been utilized to demonstrate a closed-loop hardware-in-the-loop simulation of autonomous formation control. To this end, two GPS receivers, the navigation processor and a GPS signal simulator were coupled to demonstrate a real-time control accuracy of the satellite formation in the meter range.

1 INTRODUCTION

The use of GPS as a navigation sensor for spacecraft formation flying has been demonstrated by various satellite missions, e.g. ETS-VII (Kawano et al. 2001) and Landsat-7 & EO-1 (Folta & Hawkins 2001). Promising results from these experiments have further consolidated the use of GPS as a navigation sensor and its applicability for future formation flying missions. In particular, the highly precise carrier phase measurements provided by GPS receivers are a key factor to satisfy the high-precision orbit reconstruction requirements imposed by existing or planned formations like GRACE or TechSat 21. Considering the aspect of control, it remains for the future to show that autonomous formation control, comprising formation acquisition and keeping, is a key issue to controlled formations. Nevertheless, from a long-term perspective autonomous formation control will inevitably become a topic of relevance. This is indicated by proposed missions for the next decade with demanding control accuracy requirements, like the ESA XEUS mission, which might no longer be achieved using a conventional formation control involving the satellite control center.

To fulfill these demanding requirements, a powerful navigation processor for real-time formation flying applications has been developed by the German Aerospace Center (DLR) as a test bed for the research and development in the framework of Real-time Formation Flying (RFF) applications. The real-time characteristics of the navigation processor are provided by the real-time BIRD Operating Software System (BOSS), which also acts as an interface between the processor hardware and the software applications. The preemptive nature of BOSS allows complex and computational intensive navigation and control algorithm to be executed in multiple software threads based on their assigned priorities and timing characteristics.

To demonstrate the flexible use of the navigation processor, two sample RFF applications have been implemented: a precise relative navigation task and a closed-loop formation control. The developed system allows realistic simulations of formation flying scenarios and enables through its flexible design research in various fields of formation flight, such as measurement combination and modeling investigations, dynamic algorithms selection, and orbit control strategies, aiming at a centimeter to decimeter level accuracy for the real-time relative navigation and a meter level for real-time formation control.

2 ONBOARD NAVIGATION PROCESSOR

Both the processor and the hardware interface board were designed and built by the Institute for Computer Architecture and Software Technology of the Fraunhofer Gesellschaft (FhG/First) under contract of DLR. Since the navigation processor and the board layout have successfully been flown onboard the BIRD satellite (Gill & Montenbruck 2002), the development provides a reliable platform for the development, implementation and validation of the RFF application.

2.1 Processor Hardware and Interfaces

The navigation processor features an industrial Power PC 823e processor operated at 48 MHz clock rate (without floating point support), which provides a performance of 66 MIPS. A total of 8 MB of DRAM memory are available as well as 8 MB of shadow mirror memory and 128 kB of ROM to save critical run-time parameters (Montenegro 2001). The DRAM is parity protected and duplicated which allows for error detection and correction. The RFF application software can directly be uploaded to the processor via a dedicated parallel connection located at the processor board. Run-time monitoring and logging on a remote PC is conveniently supported making use of a dedicated RS-232 interface.

The processor board is connected to an external hardware interface board, which currently provides three RS-232 connectors, supporting either three GPS receivers or two GPS receivers and a remote control PC for a closed-loop control of satellite formations. A one pulse-per-second (1PPS) connector is also available to receive 1PPS signal generated by the GPS receiver for synchronization of the onboard clock with GPS time. The time synchronization allows e.g. a proper execution of payload activities through precise command execution and contributes to a high level of onboard autonomy. Fig. 1 shows two DLR Orion GPS receivers connected to the navigation processor.

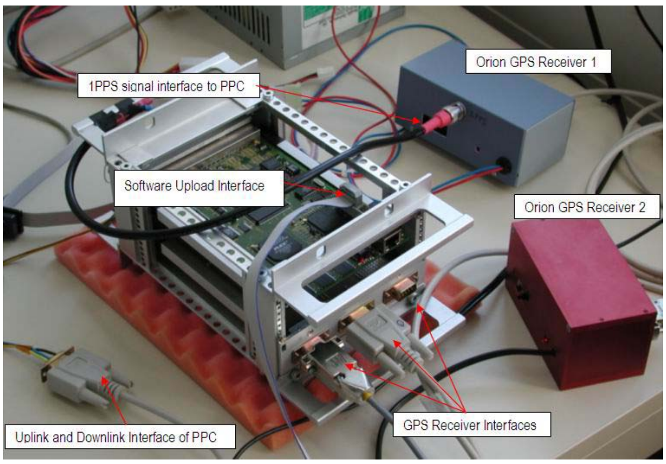

Fig. 1: Two space capable DLR Orion GPS receivers connected to the navigation processor.

2.2 The Real-Time Operating System

The real-time operating system BOSS separates the kernel run-time system and a hardware dependant layer, which allows emulation on standard Linux workstations as well as an easy adaptation to different processors. BOSS is a preemptive multitasking operating system well suited for real-time and onboard applications. Processes are executed as separate threads, which are controlled by a central scheduler based on pre-assigned priorities and timers. In this way, short and high-priority activities (e.g. commanding) can well be separated from computation intensive tasks with long duty cycles (e.g. orbit determination).

BOSS is structured in layers starting at the hardware interfaces and ending at the final application, e.g. the RFF (cf. Fig. 2). Each layer provides a virtual view from the lower layer. Above the target hardware CPU, I/O devices and other hardware units is the BOSS hardware depending layer, whose implementation depends on the actual hardware. The second layer is the BOSS kernel, which implements the interface for the applications and manages the application threads and resources. The third and top layer is the application layer where the RFF is located. BOSS is implemented in C++ and provides a C++ interface for the software application development.

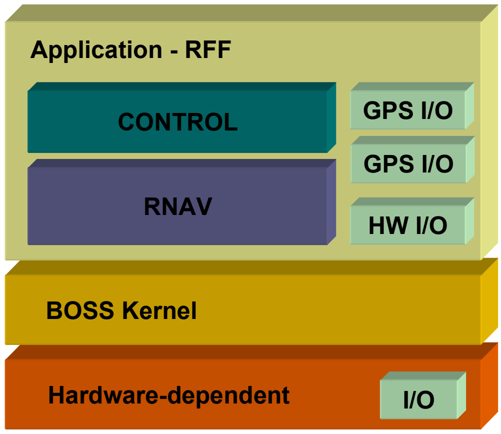

Fig. 2 : Macro structure of the BOSS operation system

3 REAL-TIME FORMATION FLYING APPLICATION

The Real-time Formation Flying (RFF) application is capable of real-time precise relative navigation and autonomous formation control. In the current development and implementation phase, there is no coupling between the two functionalities due to their complex nature. A final implementation might combine the two tasks to arrive at a powerful system for high-precision autonomous formation control.

Hardware-in-the-loop simulations of formation flying were conducted at the Formation Flight Test Bed (FFTB) (Leitner 2001) at NASA's Goddard Space Flight Center. Two DLR Orion GPS receivers were used, being connected to the navigation processor and the GPS signal simulator with two radio frequency outlets.

Orion is a L1 C/A code GPS receiver with 12 tracking channels, which has been developed at DLR based on the Mitel receiver design and employs a GP2021 correlator as well as an ARM60B 32-bit microprocessor. Originally designed for terrestrial applications, it has received numerous improvements and extensions to provide accurate and reliable tracking under a high dynamics environment. The receiver is capable to output carrier phase measurements making use of a third-order Phase Locked Loop (PLL) assisted by Frequency Locked Loop (FLL) and provides a One-Pulse-Per-Second discrete signal (Montenbruck et al. 2002). The Orion hardware, as applied in the current simulations, uses identical hardware as the Orion receiver onboard the PCsat radio amateur satellite (Montenbruck, Leung, Bruninga 2002).

3.1 Precise Relative Navigation

The relative navigation component of the RFF application provides precise absolute and relative state estimation of two spacecraft flying in formation based on raw pseudorange and carrier phase measurements. To achieve a precise absolute state estimation, single difference pseudoranges are applied to estimate the absolute position and velocity of one of the spacecraft. In contrast, the relative state is estimated from double differences of the carrier phases from all commonly viewed GPS satellites in the formation. This implies a cancellation of common error sources, such as broadcast ephemeris errors, ionospheric errors or timing errors, and thus provides a highly precise measurement type. Since the absolute and relative states are loosely coupled, the current study mainly focused on the estimation performance of the relative state.

An extended Kalman filter of dimension 24 has been designed and implemented. The filter estimates the absolute position and velocity of one of the spacecraft, the total vertical electron content of the ionosphere for this spacecraft, the relative position and velocity of the two spacecraft along with 11 pairs of possible combinations of double difference carrier phase ambiguities. A floating carrier phase ambiguity resolution technique is applied instead of the more complex and computational intensive fixed ambiguity resolution approach. However, the float ambiguity estimation requires a good a priori guess of the ambiguity to ensure rapid filter convergence. It is noted, that an accurate floating ambiguity resolution is crucial to exploit the available precision of the carrier phase measurement and hence to increase the accuracy of the relative state estimation.

The dynamics of absolute and relative motion are obtained from a rigorous integration of the satellite equations of motion making use of the Runga-Kutta 4th order algorithm (RK4). To account for an imperfect modeling of the system's state, state noise in each component is considered by increasing the covariance matrix in each step. A 10x10 Earth gravity field model is applied to ensure a sufficiently accurate propagation of the absolute and derived relative state over time frames of 20 s. Due to the precise nature of the carrier phase measurement and the imperfect modeling of the spacecraft motion, it is advisable to tune the filter in such a way as to achieve a more measurement-driven behavior which significantly shortens the time required by the filter to converge. While a measurement-driven filter tends to converge within a typical period of 5 to 10 minutes, an orbital period is normally required by a dynamic-driven filter to converge.

To demonstrate real-time relative navigation with the navigation processor, two GPS receivers were connected with the navigation processor via two RS-232 serial ports and using a radio-frequency connection with the GPS signal simulator. In the simulation setup, one GPS receiver represents the prime receiver which is collocated with the navigation processor onboard the prime satellite, while the other GPS receiver represents the second satellite in the formation. To simplify the hardware setup, the second GPS receiver is connect via a RS-232 connection replacing the inter-satellite radio link. The navigation processor collects simultaneous raw pseudorange and carrier phase measurements from both GPS receivers at one second interval, and the broadcast GPS ephemeris are transmitted to the navigation processor from the prime GPS receiver as available. These raw measurements are then fed into the relative navigation thread of the RFF. Upon measurement reception, the thread forms the single difference pseudorange and double difference carrier phase measurement, and performs the time update and measurement update as part of the Kalman filter process. To minimize the computational burden on the navigation processor, a sequential measurement update is applied to avoid large matrix operation. Fig. 3 illustrates the hardware-in-the-loop simulation setup for both the relative navigation simulation and the closed-loop formation control simulation.

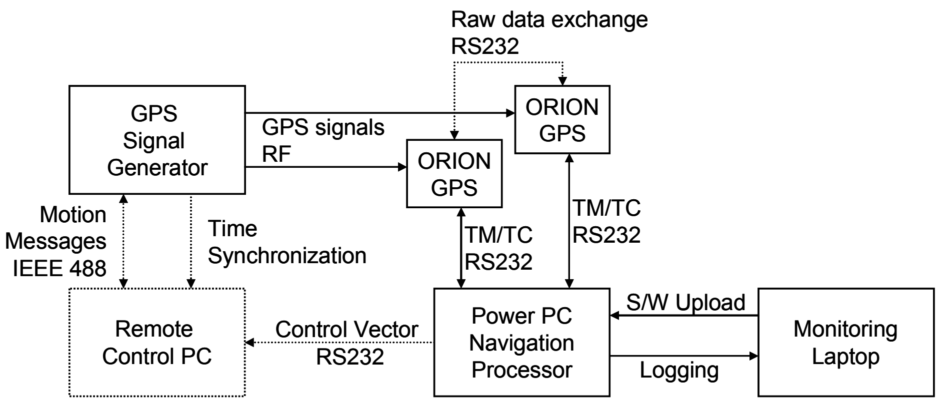

Fig. 3 : Simulation setup for the described formation flight applications. Solid lines apply both to relative orbit determination and closed-loop control setups, while dashed lines indicate the incremental hardware for the autonomous closed-loop control application.

A scenario with two spacecraft with an along-track separation of about 12 km in a near-circular orbit at 450 km altitude is employed in the simulation. Ionospheric errors and GPS broadcast ephemeris errors are taken into account by the signal simulator. Fig. 4 and Fig. 5 illustrate the relative state residuals with respect to the reference trajectory of the spacecraft available from the GPS simulator. As a result, relative navigation with a 3D RMS of 2 cm for position and 0.3 mm/s for velocity has been achieved. The relative navigation thread (RNAV) has a maximum execution cycle of approximately 9 s on the navigation processor. The execution duration of the thread is mainly governed by the number of measurements available from each channel of the GPS receivers. The RK4 integration takes approximately 0.25 s and the measurement update process for each available single difference pseudorange or double difference carrier phase measurement takes approximately 0.4 s to complete due to matrix inversion operation. The RNAV thread activates at a 20 s interval.

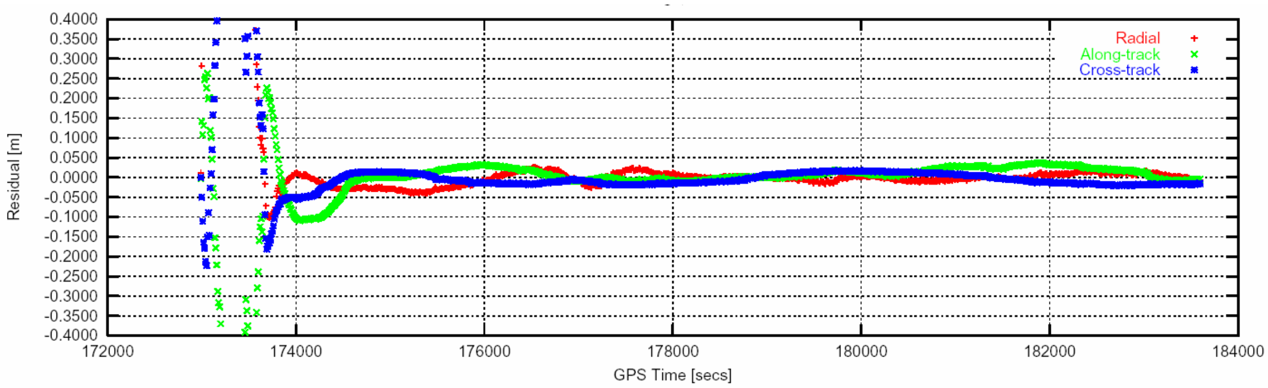

Fig. 4 : Relative position residuals from a real-time formation flying demonstration.

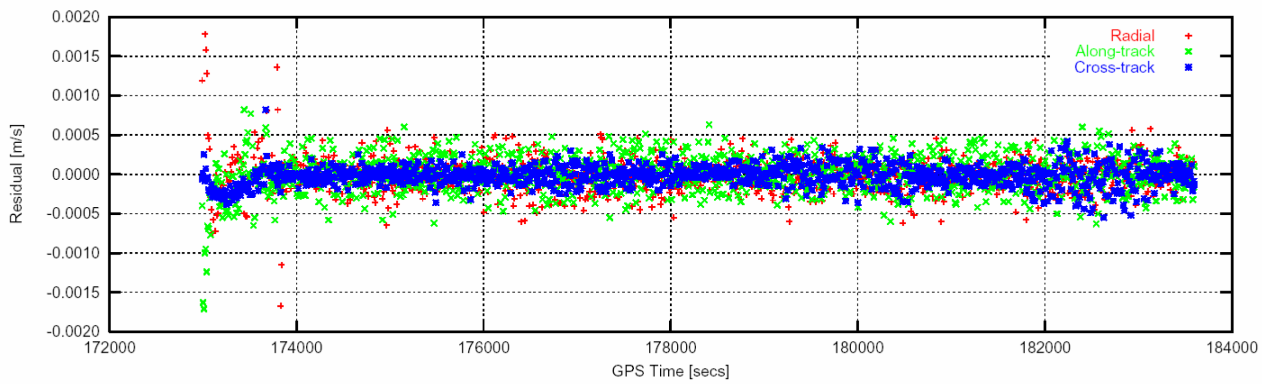

Fig. 5 : Relative velocity residuals from a real-time formation flying demonstration.

3.2 Closed-loop Autonomous Formation Control

To demonstrate a closed-loop autonomous formation control, a hardware-in-the-loop formation flight system has been established at the FFTB at NASA's Goddard Space Flight Center. The system makes use of a Spirent STR4760 GPS signal simulator using two R/F outlets to provide L1 single frequency GPS signals for two Orion GPS receivers. The Orion receivers in turn generate absolute position and velocity fixes as well as, through the exchange of raw measurements via a dedicated serial data link, their mutual relative states as derived from single difference measurements (Montenbruck et al. 2002). The Orion receivers are both connected to the navigation processor, which acts as flight computer on one of the two satellites and which executes the formation flight control function (cf. Fig. 3). Control requests from the navigation processor, comprising essentially the velocity increments for a specific satellite in the formation, are transmitted to a remote control PC using a dedicated serial interface. This PC numerically integrates the satellite states and adds the velocity increments to the orbital velocity of the satellite. The remote control PC also controls the GPS signal simulator through the provision of the current satellite states, thus closing the loop of the autonomous formation control system. While the interfaces between the GPS Orion receivers and the flight computer, as well as the flight computer and the remote control PC, are serial RS-232 connections, the interface of the remote control PC and the GPS signal simulator makes use of an IEEE 488 interface and their time synchronization is established using a dedicated timer card.

To demonstrate the performance of the developed system, a sample formation flight task has been defined and applied, which consists of a formation acquisition and keeping in low-Earth orbit. The scenario considers two satellites in near-circular near-polar orbits at 500 km altitude with an initial along-track separation of 800 m with the objective to reduce the separation to prepare for a rendezvous and docking (R&D) phase. Although a R&D scenario appears very specific, it is noted that many complex formation flight scenarios may actually be formulated in terms of a rendezvous of each of its satellites with a suitably defined virtual reference. To fully exploit the capabilities of an autonomous formation control system, a low-thrust approach with long thrusting arcs was chosen in contrast to a series of single high-thrust impulses, as usually employed in non-autonomous control scenarios. To that end, a low-thrust system, such as a pulsed plasma thruster (PPT), has been modeled which provides a thrust of 10^{-4} N and can be accommodated on a nano-satellite of 20 kg mass, as considered e.g. on the Virginia Tech nano-satellite HokieSat (Naasz et al. 2002). Based on continuous thruster operations over 10 s arcs, individual velocity increments of 0.05 mm/s may thus be requested by the control. To exploit furthermore the capabilities of a purely kinematic approach to formation control, the absolute state fixes of a single GPS receiver were applied together with the kinematic relative state fixes, as provided by two interconnected ORION GPS receivers. Making use of the existing GPS hardware, the absolute position (velocity) may be retrieved with 1 m (80 mm/s) 3Ddrms in the absence of GPS ephemeris and ionospheric errors (Montenbruck & Holt 2002). In contrast, the relative position (velocity) from the connected ORION GPS receivers delivers a superior accuracy of 0.5 m (5 mm/s) (Montenbruck et al. 2002) due to common error cancellation in the estimation of the relative state from GPS single difference measurements.

The employed control algorithm applies a non-linear feedback of Keplerian elements based on Lyapunov's direct method (Stengel 1994). Here, the relation between the control acceleration and the Keplerian elements is computed using Gauss's form of the Lagrange Planetary Equations. In addition, a mean motion control is applied (Naasz 2002) which controls along-track position differences through appropriate changes in the relative semi-major axis. Since the scenario is based on a realistic force model, the use of osculating elements in the control is prohibitive, leading to a control of the natural orbital oscillations with increased fuel consumption and reduced performance. This is effectively avoided by applying mean orbital elements in the control, which may, e.g., be derived using the Brouwer Lyddane theory (Brouwer 1959, Lyddane 1963) or NORAD's SGP4 algorithm (Lane & Hoots 1979).

Based on the above described approach, a closed-loop demonstration of autonomous formation control has been performed, covering a period of 10 h. The formation acquisition and keeping is described in terms of the spacecraft relative states which are mapped to the orbital frame for display and analysis (cf. Fig. 6). Here, the initial along-track separation of 800 m is effectively removed by changing the relative mean semi-major axis of the two orbits, as indicated by the radial component in Fig. 6. Based on an execution time on the Power PC of about 50 ms for both the Lyapunov control and the computation of mean elements, a total computation time of 150 ms was required per execution of the control thread, which was evoked every 10 s in the demonstration.

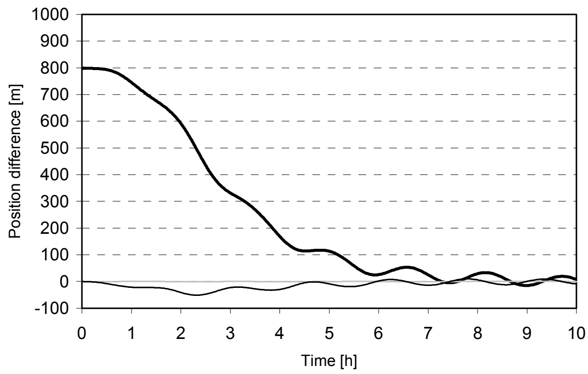

Fig. 6 : Hardware-in-the-loop demonstration of a closed-loop autonomous formation flight control in a rendezvous and docking scenario. The along-track, radial and cross-track relative positions are depicted by a bold, a thin and a gray line, respectively.

4 CONCLUSIONS

The application of a flexible and flight-proven navigation processor for real-time formation flying navigation and control is presented. The navigation processor features an industrial Power PC 823e operating at 48 MHz, which provides a performance of 66 MIPS. The navigation processor comprises an external hardware interface with three RS-232 and one 1PPS signal interface supporting up to three GPS receivers or two GPS receivers and one remote control PC for closed-loop formation control simulations. The BOSS real-time operating system acts as an interface between the processor hardware and the software applications and, through its preemptive nature, it is especially well-suited to handle complex and computational intensive software applications.

The navigation processor provides a reliable platform for the development and testing of the flexible formation flying applications. Current implementations of formation flying applications support precise relative navigation as well as autonomous formation control, as demonstrated in a series of hardware-in-the-loop simulations. The precise relative navigation of a satellite formation using GPS has been demonstrated at a level of two centimeters. In addition, an autonomous formation control with an accuracy of 5 m has been achieved using a closed-loop simulation system, which validates the possibility of autonomous formation control for formations with a minimum separation of as close as 50 m.

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