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PRISMA: An In-Orbit Test Bed for Guidance, Navigation, and Control Experiments

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This paper presents system-level hardware-in-the-loop real-time simulation results for three different guidance, navigation, and control experiments designed for in-flight demonstration on the PRISMA formation-flying satellite mission. The mission consists of two spacecraft: Main and Target. The Main satellite has full orbit control capability, whereas Target is attitude-controlled only. Launch is planned for November 2009. The simulation results presented demonstrate the feasibility and readiness for flight as well as the expected in-flight performance. The three experiments include Global Positioning System and vision-based formation flying for two spacecraft in both passive and forced motion. In addition to these simulation results, the paper gives an overview of the PRISMA mission in general and the guidance, navigation, and control experiments in particular. The hardware-in-the-loop real-time test environment is also presented.

Nomenclature

A^*	=	graph search algorithm
l_1-norm	=	rectilinear distance

I. Introduction

THIS paper presents system-level real-time hardware-in-the-loop simulation results for three different guidance, navigation, and control (GNC) experiments designed for in-flight demonstration within the PRISMA formation-flying satellite mission [1,2]. The mission is an in-orbit technology test bed that implements GNC strategies for advanced formation flying and rendezvous. The objective of the PRISMA mission is to develop and qualify new technology necessary for future space missions. This concerns both hardware qualification and several sets of GNC experiments for formation flying. By the spring of 2009, PRISMA is about to complete its system test campaign, and launch is planned for November 2009.

The three GNC experiments presented here include Global Positioning System (GPS)- and vision-based formation flying for two spacecraft in both passive and forced motion. The two first experiments consist of GPS-based passive autonomous formation flying (AFF) and GPS- and vision-based forced-motion proximity operations (PROX) and final approach/recede maneuvers (FARM). These two groups of experiments are based upon a model-predictive control (MPC) framework, as described in [3]. The third experiment is a completely autonomous rendezvous experiment designed to mimic a Mars sample and return scenario. This experiment is described in greater detail in [4].

A number of missions have previously demonstrated rendezvous and docking aspects of spacecraft formation flying. The Engineering Test Satellite VII [5,6] provided an early demonstration of GPS-based autonomous rendezvous and docking. The Experimental Satellite System 11 [7,8] operated a lidar to perform rendezvous with several launcher upper stages and nonoperational satellites. The mission is developed by the U.S. Air Force and very little information is publicly available. Perhaps the most noted mission during recent years is Orbital Express [9,10], which demonstrated several aspects of on-orbit servicing, inspection, and rendezvous and docking. The contents of these missions overlap to some extent with the GNC experiments of PRISMA. However, the GPS-based experiments on PRISMA emphasize passive formations and forced motion under flight constraints. The vision-based experiments on PRISMA use a low-cost sensor that is implemented within the autonomous star tracker. This sensor is used to demonstrate both cooperative and noncooperative aspects of navigation. In addition, the rendezvous experiments on PRISMA are performed without laser-based distance measurements, and at far distances, navigation is based on angles only.

The simulation results presented in this paper belong to the onboard software system-level tests performed as part of the system qualification for flight. There are several approaches to hardware-in-the-loop demonstration of multispacecraft missions. For example, [11] describes an advanced test bed with spacecraft simulators floating via air pads on a flat floor. This environment demonstrated autonomous vision-based docking and proximity operation maneuvers for the Orbital Express mission. The approach allows for a large amount of flight-representative hardware in a closed loop but has limitations in representing the full degrees of freedom and representative orbital dynamics. A different approach is made in [12], in which a robotic arm is used to represent the true spacecraft motion and geometric conditions. The environment described in [13] uses GPS receivers fed by radio frequency (RF) signals in a closed loop. A predecessor of this environment is used in [14] to demonstrate the GPS navigation system for the Gravity Recovery and Climate Experiment (GRACE) mission. The PRISMA GPS navigation function is a development based on GRACE.

The work presented here demonstrates the expected in-flight performance for the GNC experiments of the PRISMA mission by the use of a much simpler hardware-in-the-loop environment. The environment is used for software system tests and includes a computer and data communication bus with full flight-representativeness. The test environment architecture allows for gradual expansion with more hardware in the loop, and in the flight-model spacecraft system test campaign, the environment includes the complete spacecraft avionics in the loop and can even be used with RF GPS signals in a closed loop. The simulation environment is

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based on experience from the SMART-1 mission, both in terms of simulation environment and flight results [15,16]. In addition, separate verification of the GPS-based navigation function is also performed [17]. For these reasons, the system-level simulations are believed to have high relevance in terms of expected flight performance, and the simulations demonstrate in this way the feasibility and flight-readiness for these GNC experiments.

The paper is organized as follows: First, an overview of the PRISMA mission is given. Then the GNC systems on the two PRISMA spacecraft are briefly described. This is followed by a short description of the three GNC experiment sets. The paper then describes the system-level test setup. After this, the paper presents the system-level test results for the three experiment sets. Finally, some conclusions are made.

II. Overview of the Mission

The PRISMA mission consists of two spacecraft: Main and Target. Details on the mission in general can be found in [1,18,19]. The Main spacecraft is 3-axis-stabilized and is equipped for full delta-V maneuverability, independent of the spacecraft's attitude. With the nominal hydrazine propulsion system, Main will have a total impulse corresponding to 100 m/s. The exterior dimensions of the Main central body are $750 \times 750 \times 820$ mm. In deployed configuration, the distance between the tips of Main's solar panels is 2600 mm. The Target satellite is also 3-axis-stabilized but with a simplified magnetic attitude control system. The Target spacecraft does not have any orbit maneuver capability. The dimensions of the Target body are $570 \times 740 \times 295$ mm. The launch mass of the two spacecraft is limited to 200 kg. Main is currently estimated to be 145 kg and the mass of Target is 40 kg. An impression of the two spacecraft in orbit is shown in Fig. 1.

Apart from its nominal hydrazine propulsion system, PRISMA has two different payload propulsion systems: the high-performance green propellant (HPGP) [20] and a micropropulsion system [21]. There are three payload sensor systems used for formation flying on PRISMA: the vision-based sensor (VBS) [22,23], the GPS navigation system [24–26], and an RF-sensor system [27,28]. The vision-based sensor is implemented as part of the onboard autonomous star tracker. The GPS navigation system includes standard commercial receivers with modified navigation software. As a part of the GPS navigation system, a high-fidelity navigation filter is developed and executed on the spacecraft's onboard computer [17]. Main also carries a digital video system used to observe and document the formation-flying experiments. The sensor systems are accommodated for in-flight qualification as such, but are also used in a series of closed-loop GNC experiments conducted by the different organizations participating in the mission [2,18,24–28].

Table 1 summarizes the primary objectives of the PRISMA mission along with references that further describe these experiments in more detail. Both GNC experiments and hardware-related experiments are shown in the table. The GNC experiment sets are divided into two different groups: passive formation flying and forced motion. Passive formation flying corresponds to experiments that make use of the natural orbit period to obtain a relative motion between the Main and Target spacecraft. The orbit control then consists only of maneuvers with the purpose to maintain this natural relative motion. The forced motion corresponds to experiments in which a relative motion between the two spacecraft is arbitrary in the sense that it is not constrained by the relative orbit dynamics. The autonomous rendezvous experiment contains parts that are passive, but its fundamental characteristics are more of a forced type.

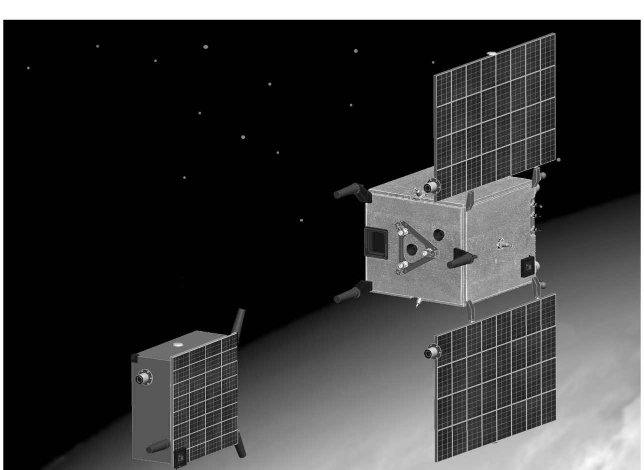

Fig. 1 Artist's impression of the PRISMA satellites in orbit.

Table 1 PRISMA primary mission objectives

GNC Experiment Sets	References
Passive formation flying	
Autonomous formation flying	[1–3]
Autonomous formation control	[24–26]
RF-based formation flying	[27,28]
Forced motion	
Proximity operations final approach/recede maneuvers	[1–3]
Forced RF-based motion	[27,28]
Autonomous rendezvous	[1,2,4]
Hardware-related tests	
HPGP motor tests	[20]
Microthruster tests	[21]
VBS sensor tests	[23]
RF sensor tests	[27,28]

In addition to the primary objectives presented in Table 1, the secondary mission objectives of the PRISMA mission are as follows:

1) Provide a test flight for a newly developed system unit and a power control unit with battery management electronics.

2) Act as a test project for new model-based development of onboard software [29].

3) Demonstrate autonomous orbit keeping of a single spacecraft.

Three GNC experiment sets among the primary mission objectives are under the responsibility of the authors: AFF, PROX/FARM, and autonomous rendezvous (ARV). The following sections give an overview of the GNC platform and briefly present these three GNC experiment sets.

III. GNC Platform Overview

PRISMA is designed for launch in a sun-synchronous orbit with 700 km altitude and 1800 or 0600 h ascending node. The two spacecraft are launched together with Target separation from Main after an initial phase of commissioning. This section gives an overview of the GNC systems on the Main and Target spacecraft.

A. Main

The Main spacecraft has both attitude and orbit control capability. It is equipped with sun sensors, magnetometers, coarse rate sensors, an autonomous star tracker, and a set of accelerometers. The actuators are magnetic torque rods, reaction wheels, and hydrazine thrusters. The basic attitude control functionality is based on the SMART-1 attitude control system [15,30].

There are six 1 N nominal hydrazine thrusters arranged in three perpendicular pairs of oppositely directed thrusters. In addition to these thrusters, there is a fourth oppositely directed pair of HPGP thrusters. This pair is aligned such that it can replace any of the nominal pairs, still providing full 3-dimensional delta-V capability, but sacrificing the perpendicularity. The HPGP thrusters will be used both as redundancy and for in-flight qualification.

The Main spacecraft mode architecture is illustrated with Fig. 2. There is basically one mode for each group of GNC experiments, as given in Table 1. There is also a safe mode that provides attitude safety as well as safe orbit control. The AFF mode is used as a hub among the operational modes. The AFF mode is particularly useful for this purpose because it is based on passive formations. The

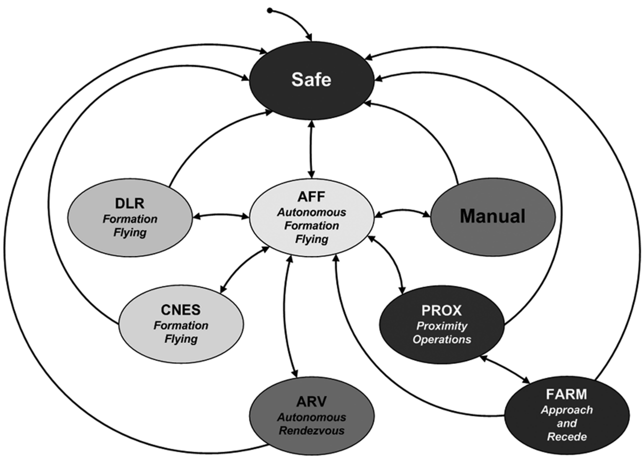

Fig. 2 Main spacecraft mode architecture.

formation can in this way be parked in this mode if necessary during the process of going between the other operational modes. An additional reason for using the AFF mode as such a transition mode is that it uses the GPS navigation system [17]. This system is a fundamental part of the mission, not only for the AFF mode and for the autonomous formation control experiments, but also for the safe orbit control [31] functionality, which is active in the safe mode. As opposed to the AFF mode, safe orbit control selects an orbit that will be collision-free even, if it not is actively maintained.

B. Target

The Target spacecraft does not have orbit control capability. It is 3-axis-stabilized and has an attitude control system that is based on sun sensors, magnetometers, and magnetic torque rods. Target has two operational modes: the sun acquisition and safe mode and the normal mode. The normal mode is used to point the spacecraft in an attitude profile that is a tradeoff between having the solar panels oriented toward the sun and having one of the GPS antennas pointing toward zenith. The normal mode can also point along an attitude profile that mimics a tumbling motion. This will be used in parts of the VBS experiments to resemble a noncooperative tumbling rendezvous Target. The Target attitude control system is described in more detail in [18,32].

IV. GNC Experiments

This section describes the three different GNC experiment sets: autonomous formation flying, proximity operations and final approach/recede maneuvers, and autonomous rendezvous. These three experiment sets have been selected because they represent important model missions.

The autonomous formation flying experiments represent missions that include passive apertures and loose formations. They also represent phases and situations occurring in on-orbit assembly and on-orbit inspection.

The proximity operations and final approach/recede maneuvers experiments can mimic navigation about a large space structure. Typically, this occurs in on-orbit servicing, on-orbit inspection, and on-orbit assembly in near-Earth scenarios.

The autonomous rendezvous experiments are designed to represent a Mars sample and return (MSR) mission. The subsequent sections describe each of these three experiment sets.

A. Autonomous Formation Flying

The AFF experiment set consists of passive formation flying based on GPS navigation. The experiments are implemented in the AFF mode of the Main spacecraft. The GPS-based navigation function is further described in [17,26]. It consists of a navigation filter that can be essentially described as an extended Kalman filter for which the measurement inputs are the pseudoranges coming from the GPS receivers on Main as well as on Target. The filter provides the Main and Target states. When the receivers on Main and Target see the same set of GPS satellites, the states coming from the filter will be correlated so that the difference between the states will have an accuracy that makes use of the relative GPS properties. The filter itself makes use of high-order Earth gravity models as well as modeling of drag and solar pressure to achieve its desired accuracy. Proving the performance of the filter is one of the fundamental parts of the PRISMA mission, and it is believed that the relative navigation accuracy will be below 0.1 m. The simulations performed so far indicate that this is fulfilled, except for some occasions when thrusting is frequent. In these cases, the error can reach up to 0.2 m.

The orbit guidance function used in the AFF mode takes as input the position and velocity for a relative trajectory. It also needs to be commanded with the true anomaly for when the relative state should become active. The state defines the passive orbit for Main relative to Target. A MPC framework is used on the ground to optimize the operational sequence of passive orbits. The AFF orbit guidance function also handles entry to the mode from any other mode to the closest passive parking orbit. This function enables the AFF mode to take a triggered autonomous entry from higher modes, rather than triggering a more dramatic safe-mode entrance.

The AFF mode uses a feedback orbit control function [3]. This function is also based on MPC taking as input up to seven planning relative position coordinates, times, and control boxes. The MPC function optimizes the next control request based on propagation over the planning points. Propagation is implemented for the general case of elliptical orbits [33]. Constrained fuel optimization in terms of l_1-norm is performed onboard as two simplex problems with 60 and 30 variables and with 24 and 12 constraints, respectively, for the out-of-plane and in-plane control. The feedback orbit control function requests a certain impulse from a thruster command distribution function, which calculates the commands to each individual thruster, taking into account spacecraft attitude as well as distribution in time of the pulse if too large for commanding in one single 1 Hz execution cycle. The AFF experiments will consist of in-plane and out-of-plane relative orbits ranging from a few kilometers down to a few tens of meters, possibly also going down to 10 m distances.

B. Proximity Operations and Final Approach/Recede Maneuvers

The PROX and FARM both consist of forced-motion flight of Main around Target. In the PROX experiment set, the Main spacecraft flies in forced motion around a virtual structure defined about the Target spacecraft. The purpose of the virtual structure is to mimic the circumflight about a large object with appendages and no-fly zones, such as the International Space Station (ISS). There are two branches of PROX. One branch is based on the GPS measurements and the same navigation function as used in the AFF mode. The other branch uses VBS measurements of the relative position and also the relative pose of Target. The measurements are filtered in the Main onboard software to better estimate the relative states and to make the experiment more robust to temporary measurement dropouts. The VBS-based branch is in turn divided into one cooperative part and one noncooperative part. For the cooperative part, Target will flash a light-emitting diode (LED) pattern, which is observed by the VBS camera unit on Main. The noncooperative VBS navigation uses a priori information about geometrical features and dimensions of the Main spacecraft to estimate its relative position and pose.

The PROX orbit guidance function uses an uplinked roadmap containing all the allowed points and paths between points around the virtual structure. The roadmap is intended to represent allowed flight regions around for example the ISS. A navigation plan is then commanded containing the different goal points in the map that should be visited by Main and the desired times for when to reach these points. The PROX guidance function calculates from these inputs the optimal path with the use of an A^* algorithm. The roadmap and virtual structure are illustrated in Sec. VI.B.

The FARM experiment consists of going from one of the points of the roadmap along a straight line to a delivery point close to the Target spacecraft. This part of the experiments uses cooperative LED-based VBS measurements only. The PROX experiments are intended for distances from 100 down to 10 m. The FARM experiment will take the Main spacecraft from around 10 m down to less than 1 m. For this purpose, there is a dedicated rendezvous surface on Target with a special LED pattern that allows full relative pose determination. The FARM orbit guidance function is commanded with a start point (being one of the points on the roadmap) and an end point and velocity near the Target spacecraft body.

As in the AFF experiments, the MPC-based feedback orbit control function is also used for the PROX/FARM experiments. However, for these experiments, the planning horizon is much shorter. The control function implementation is, however, made general enough to handle such different applications.

C. Autonomous Rendezvous

The ARV experiment set demonstrates a complete autonomous rendezvous starting with Main about 25 km away from Target. The Main spacecraft will then maneuver autonomously down to a few tens of meters from Target, ending the experiment with a final approach to within 1 m. The final steps will make use of the PROX/FARM functionality described in the previous section.

The purpose of the ARV experiment set is to mimic an MSR mission so that Main will autonomously locate the Target spacecraft and perform a series of orbit-aligning, closing, and homing maneuvers to finally get within a distance from Target that allows the PROX/FARM functions to take over. All of these maneuvers are performed using VBS-based orbit navigation only [34].

The ARV will be based on optical navigation using the VBS [22,23]. The data processing of the VBS is either executed on the redundant star-tracker processing unit or on the processing unit used for star tracking at the same time as the star-tracker function. The VBS uses one long-range and one short-range camera unit. The long-range camera can deliver inertial direction to the Target spacecraft from up to 10,000 km down to somewhere around 10 m. From approximately 100 m and below, the light on the charge-coupled device emerging from the solar illumination of Target will blind the observation of surrounding stars, thus making inertial determination of Target's location impossible using this camera only. In this case, the two attitude-determination cameras are used in combination with the long-range VBS camera. The short-range camera is used from a few tens of meters down to less than 1 m.

At the start of the ARV experiment, the Main orbit is assumed to be known and propagated onboard. A rough estimate of Target's orbit is also known and propagated onboard Main. These initial conditions correspond to a real MSR case in which Main would be the Mars orbiter for which the orbit will be well known. Target represents the sample canister for which the launch parameters will provide a coarse orbit estimate. The ARV experiment then starts with the autonomous detection of Target using the VBS. This is done by scanning the Earth limb with the VBS long-range camera.

An orbit navigation filter is then initialized to improve the knowledge of the Target orbit. This Target orbit-determination (OD) filter will be initialized with the rough estimate of the Target position and velocity coming from the onboard Target orbit propagator. The Main orbit propagator serves as reference and is used together with the VBS angular measurements to update the OD filter.

When the OD filter has converged, a switch to the Main navigation (MN) filter takes place. This filter estimates the Main state relative to Target. The estimate from the OD filter now reinitializes the onboard Target orbit propagator, which is used with the VBS measurements for updating the MN filter. The OD and MN filters are partly based on [34], and the MN filter time update is based on [31].

At this stage, Main will start to maneuver to align its orbit with Target's orbit. This is achieved using algorithms based on the method described in [35]. When orbit aligning is done, Main will have about the same mean Keplerian elements as Target, except for the mean anomaly, which is not adjusted at this stage.

Then Main starts the approach toward Target using V-bar hops. The technique is based on solving equations using [31]. This closing phase will take Main close enough to Target for the VBS system to resolve relative pose and position between the two spacecraft. The final distance in the closing phase will be about 30 m.

Once the closing phase is complete, the final steps are performed using the optical branch of the PROX and the FARM functionality, as described in the previous section. The ARV experiment ends with a recede maneuver taking the Main spacecraft from the 1 m closest distance back to a passive orbit on the V-bar at about 30 m distance between the two spacecraft. The ARV experiment is described further in [4].

V. System Test Setup

Testing of the PRISMA GNC subsystem is based upon the approach taken in SMART-1 [16]. Apart from pure functional software unit tests of each module, the tests are divided into software system tests and spacecraft system-level tests.

A. Software System Tests

The software system tests are performed in a real-time hardware-in-the-loop software validation facility called SATLAB. The environment is illustrated with the schematic shown in Fig. 3. SATLAB consists of an engineering model of each of the computer boards of Main and Target. These boards include the complete onboard software, because all software functions including GNC are handled by single processor computers. The computer boards are based on LEON processors and belong to the complete data handling system. In the real case, the computer boards are connected to the sensors and actuators via a controller area network (CAN) bus and interfacing electronics called remote terminal units (RTUs). In the SATLAB environment, the CAN bus is connected to a system-level spacecraft simulator SatSim, which emulates these RTUs, sensors, actuators, orbital and attitude dynamics, as well as the space environment for the two satellites. The simulator also emulates the intersatellite communication link. The computer board for Main has an integrated telemetry/telecommand board so that it can be commanded from the RAMSES [36] electrical ground support equipment software. The same software is going to be used as the Main software for flight operations.

The complete onboard software is developed in MATLAB/Simulink from which C-code is automatically generated using Real-Time Workshop. This includes packet-utilization-standard-compliant software with Consultative Committee for Space Data Systems ground communication; failure detection, isolation, and recovery; power and thermal control; and the GNC software. The GNC software also includes deliveries from the other GNC experiment participants.

The SatSim is developed in a similar way but under the xPC Target environment. It is executed on a standard PC equipped with a CAN interface board and User Datagram Protocol and Internet Protocol connections toward RAMSES. In this way, true simulated quantities

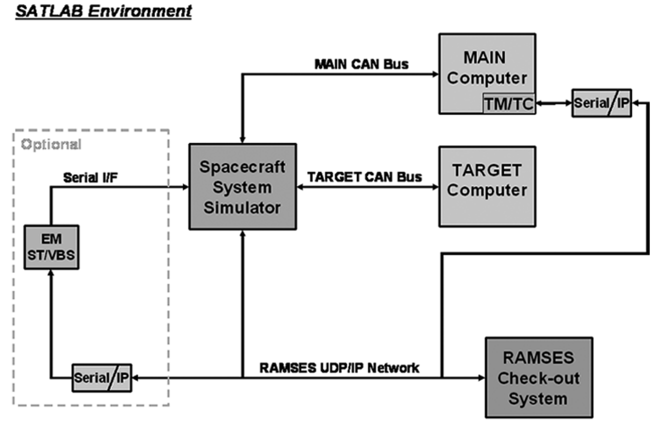

Fig. 3 Schematic of the SATLAB real-time software validation facility.

can be observed beside the onboard estimates during testing. From RAMSES, it is also possible to inject errors into the simulator via this communication interface. Through an RS422 board, an engineering model star tracker can be included in the loop as well as time reference pulses from simulated GPS receivers and RF instruments.

The test campaign consists of commissioning of Main and Target, Target separation from Main, and simulations of each of the GNC modes representing all the closed-loop experiments. Test cases are designed using PLUTO [37] command and monitoring scripts in RAMSES to keep results reproducible.

B. Spacecraft System Tests

The spacecraft system-level test campaign includes a series of tests performed on the flight-model spacecraft. For the GNC subsystem, there are two Main groups of tests: open-loop and closed-loop.

Open-loop tests verify the correct sign of the response of all different sensor-to-actuator loops. This is done by stimulating the sensors and looking at the response from the software as well as independent detection of the actual response of the actuators. Dedicated open-loop tests are performed for the GPS and VBS. The GPS navigation function is verified with a GPS signal simulator that can simulate the RF signals seen by two vehicles (antennas) in a synchronized way. The GPS signal simulator is used to generate RF signals representing the respective antennas on Main and Target. The VBS will be verified with the real Target spacecraft for the close range, but with reduced strength illumination. The long-range VBS functionality is verified with a dedicated stimulator.

Closed-loop tests consist of a subset of the tests executed in the software system test campaign. The difference in this setup is that the real flight-model spacecraft computers, CAN buses, and interface electronics are used. The sensors are replaced with platform unit simulators (PUSIMs) that are connected to the SatSim via UDP/IP. These PUSIMs generate electrical analog signals and serial communication corresponding to the true sensor. A schematic of the closed-loop setup is shown in Fig. 4.

VI. System Test Simulation Results

This section presents simulation results from the software system test environment SATLAB as described previously. These results are obtained with the complete onboard software executed on a flight-representative computer connected via a CAN bus to the full spacecraft system simulator SatSim.

Three experiments are presented: one AFF experiment, one PROX experiment, and one ARV experiment. Several of the results are presented in spacecraft local coordinates. For these transformations, the curvilinear transformation of [38] was used.

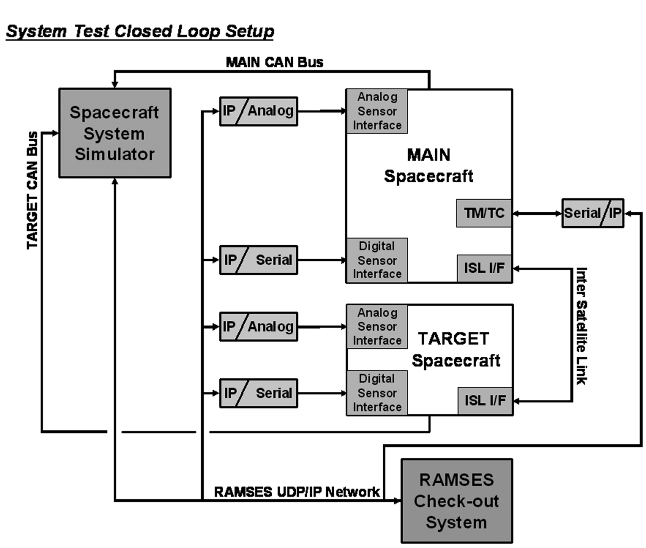

Fig. 4 Spacecraft system test setup schematic (IP denotes Internet Protocol, ISL denotes intersatellite link, and I/F denotes the interface).

A. Autonomous Formation Flying

The AFF example shown in this section implements a relative orbit that is a stretched-out ellipse centered 3 km behind Target. The ellipse spans ± 2 km around its center and varies ± 1 km in radial direction. The ellipse also has a slight cross-track extension of less than ± 50 m. The relative trajectory is shown in Figs. 5–7. The figures show the spacecraft local relative trajectory for the AFF example. Three different plane projections are shown, and delta-V maneuvers are indicated as light gray short lines.

The control errors are presented in Fig. 8. The figure shows the control errors together with dashed lines indicating the associated control box, and delta-V maneuvers are indicated in light gray. The figure shows that some excursions are made outside of the control

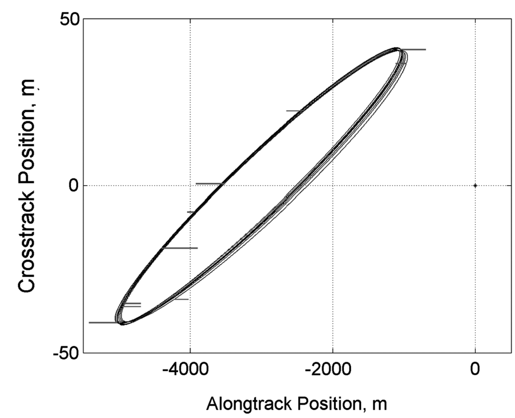

Fig. 5 AFF relative orbit: along-track/cross-track projection.

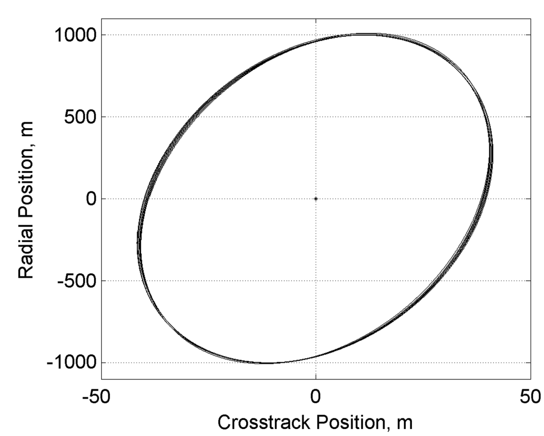

Fig. 6 AFF relative orbit: cross-track/radial projection.

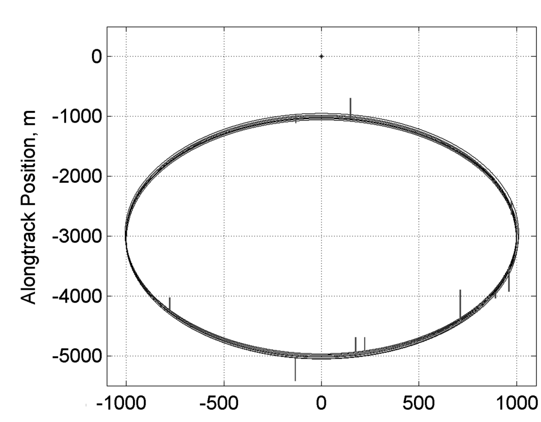

Fig. 7 AFF relative orbit: radial/along-track projection.

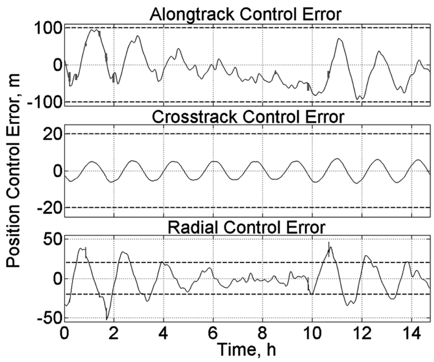

Fig. 8 AFF control error.

box in the radial direction. This is a result of the control law being set to allow delta-V maneuvers at predetermined times only. This function can be switched off to permit delta-V maneuvers immediately when the control box bound is violated. Position and velocity navigation errors are presented in Fig. 9. This figure shows the GPS navigation filter position errors. The delta-V maneuvers are indicated as gray vertical lines. The corresponding velocity errors are shown in Fig. 10.

B. Proximity Operations

The PROX example consists of maneuvering, by use of GPS navigation, around a virtual structure centered at Target's position. The example ends with holding Main in a point slightly out of Target's orbit plane. The relative flight trajectory, flight map, and virtual structure are illustrated with Fig. 11. The flight trajectory is shown as a solid black line. The flight map can be seen as black nodes connected by straight gray lines. The space-station-like shape is the associated virtual structure. Note that the flight map has been laid out with respect to the virtual structure and that Main only has onboard knowledge of this map and not of the virtual structure itself.

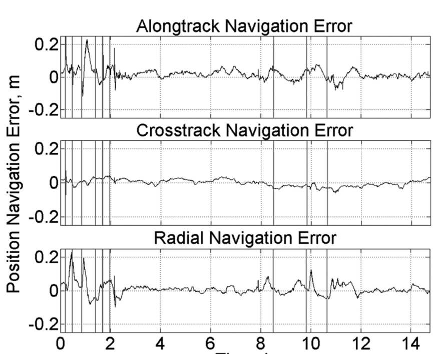

Fig. 9 AFF navigation position errors.

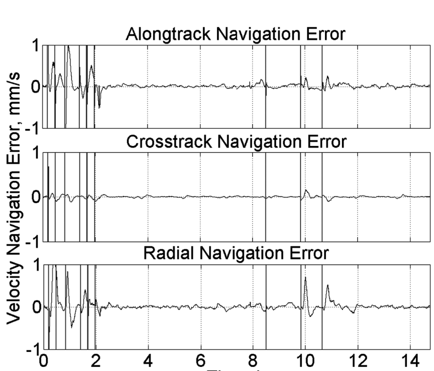

Fig. 10 AFF navigation velocity errors.

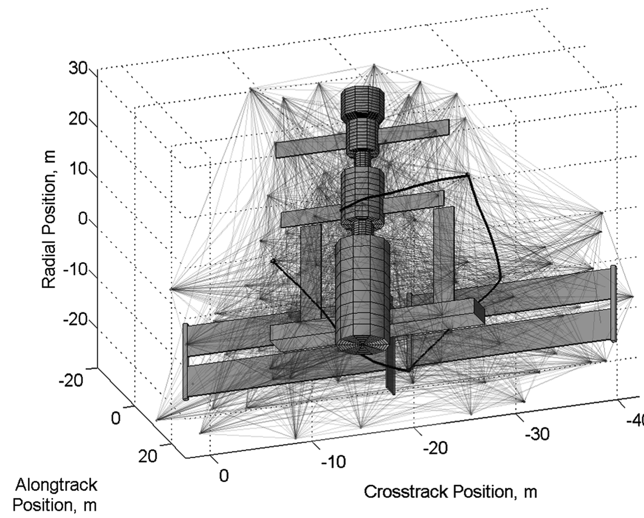

Fig. 11 PROX experiment trajectory and virtual structure.

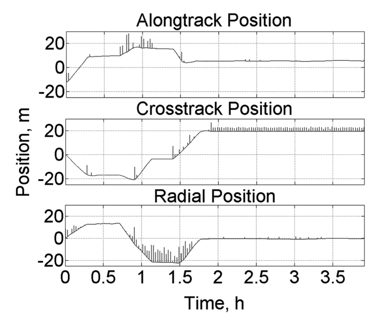

Fig. 12 PROX experiment trajectory.

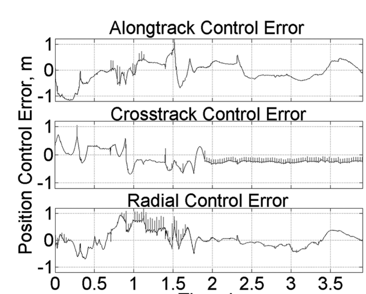

Fig. 13 PROX experiment control errors.

Figure 12 shows the relative trajectory as a function of time. The delta-V maneuvers are indicated in gray. The figure shows that the holding starts after 1.8 h and that this costs significant cross-track delta-V. Figure 13 shows the control errors, with delta-V indicated in gray.

C. Autonomous Rendezvous

The ARV experiment shown here starts in the orbit-aligning phase at a distance of 25 km from Target. The experiment ends with a PROX/FARM maneuver going to less than 1 m from Target, followed by a retraction maneuver to go slightly further away.

Figure 14 shows the relative trajectory for the complete experiment with the different phases or ARV submodes indicated. The figure shows that in the orbit-aligning phase, the cross-track and radial differences are reduced and that the along-track difference is reduced in the closing phase by the use of radial hops. In the end of the closing phase, the two spacecraft are close enough to each other to

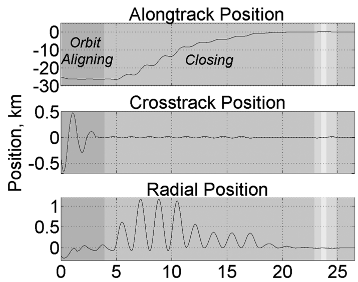

Fig. 14 ARV experiment relative trajectory.

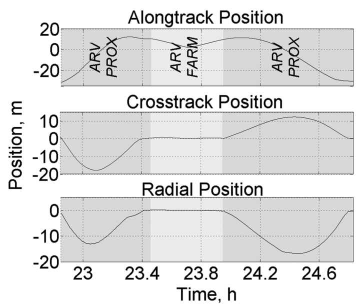

Fig. 15 ARV experiment PROX/FARM relative trajectory.

allow the VBS to provide full distance and pose information. Figure 15 shows a close-up of relative trajectory for the PROX/FARM part of the experiment. Unlike the GPS-based PROX example shown in the previous section, the PROX/FARM experiment performed here is based on the VBS.

Figure 16 shows the navigation errors for the orbit-aligning phase. The figure shows how the initial along-track uncertainty is successively reduced. Figure 17 shows the navigation errors for the closing phase. The figure illustrates how the along-track estimation error remains until the end of the phase, when the two spacecraft come very close to each other.

Figure 18 shows the navigation errors during the PROX/FARM phase of the ARV experiment. The error is very small, except for during two intervals when it starts to grow. This is a result of Main

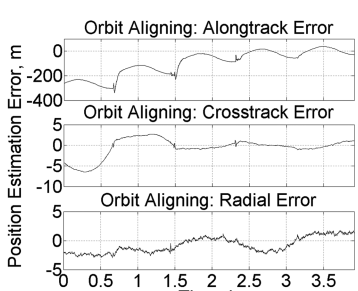

Fig. 16 ARV estimation error during the orbit-aligning phase.

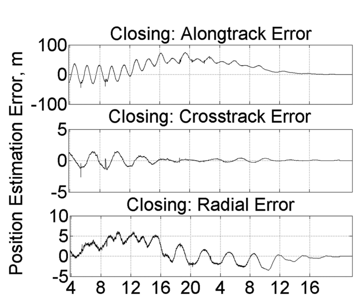

Fig. 17 ARV estimation error during the closing phase.

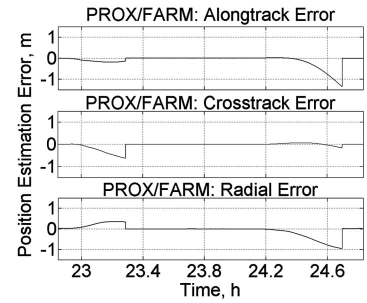

Fig. 18 ARV PROX/FARM estimation error.

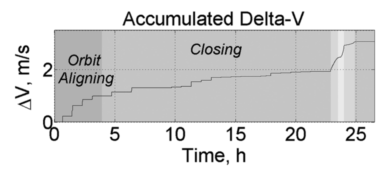

Fig. 19 Accumulated delta-V for the ARV experiment.

flying above Target in the approaching as well as receding part of the PROX. While doing so, it pointed the VBS toward Target with the Earth in the background. Because the modeled VBS was not able to deliver measurements with the Earth in the field of view, the navigation was based on propagation with a growing error as a result.

Finally, Fig. 19 shows the accumulated delta-V for the ARV experiment presented. The delta-V for the actual rendezvous is less than 2 m/s and the forced motion during PROX/FARM adds 1 m/s to this.

VII. Conclusions

This paper has presented real-time hardware-in-the-loop software system-level test results from three of the guidance, navigation, and control experiments to be performed on the PRISMA formation-flying mission. The paper has also presented an overview of the PRISMA mission, the experiments, and the test environment.

The results presented in this paper are a part of the software system-level test campaign in the mission. This test campaign is an essential part of the system flight qualification, and the results demonstrate the feasibility and flight-readiness of the formation-flying experiments as well as the expected in-flight performance of the PRISMA mission.

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