DESIGN AND PROTOTYPING OF PROBA-3 FORMATION FLYING SYSTEM

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Abstract: *This paper describes the Formation Flying System of PROBA-3 as it has been developed and prototyped during phase B of the project. PROBA-3 will demonstrate the Formation Flying technology along with on-board autonomy for two spacecraft in highly elliptical orbit. After a description of the architecture and the main modules of this software: Failure Detection Isolation and Recovery for Formation, GNC for Formation, GNC for spacecraft, Formation Flying Manager, the integration process of the Formation Flying Software is presented along with tests results.*

Keywords: *PROBA-3, Formation Flying System, GNC, Design, Prototyping.*

1. Introduction

The PROBA-3 mission aims at demonstrating in-orbit the techniques of Formation Flying (FF). It consists of two spacecraft, the coronagraph spacecraft (CSC) and the occulter spacecraft (OSC) flying in a high elliptical orbit around the Earth. The orbital elements of the OSC are presented in Tab. 1 below:

Table 1. Orbital elements of the OSC

Parameter	Value
Perigee height	600 km
Apogee height	60530 km
Semi-major axis	36943 km
Eccentricity	0.8111 -
Inclination	59°
Right Ascension of the Ascending None	84°
Argument of Perigee	188°
Orbital period	19h38m
Launch date	2016

The nominal orbit is divided into the following main parts, as presented in Fig. 1. During the apogee arc, formation flying experiments are performed, in a low-perturbation environment. At the end of the apogee arc, some 3 hours after apogee, a two point transfer manoeuvre is performed to prepare the following formation reacquisition, after perigee. During the perigee arc, the spacecraft are in free flight. Finally, the formation is reacquired some 3 hours before apogee, to start new FF experiments. The foreseen Formation Flying experiments are station keeping and rigid/loose resizing and retargeting manoeuvres. A scientific payload, the coronagraphy instrument, takes advantage of the station keeping to study the Sun corona.

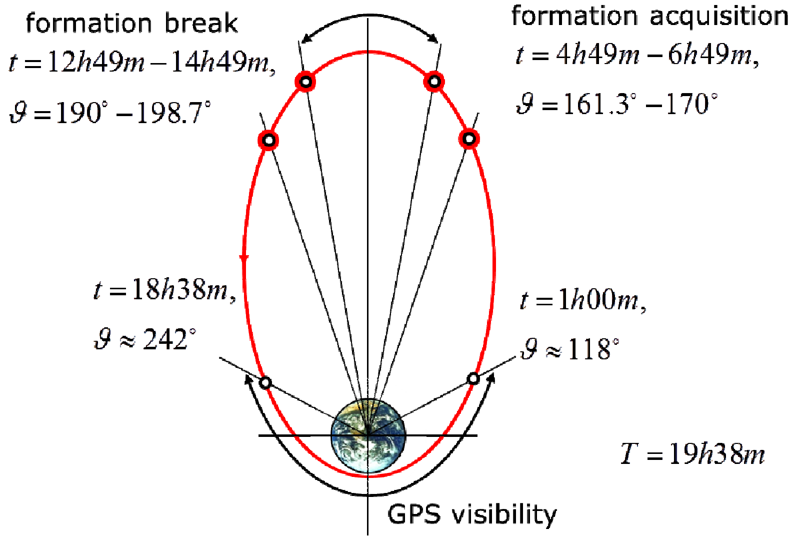

Figure 1. Orbital routine

In order to perform Sun coronagraphy while in station keeping, and to demonstrate the precision of the formation flying, the mission requirements for the accuracy in rigid phases is of the order of millimetres for position error and arcsec for attitude errors. Consequently, very accurate optical sensors are used, that also require a high accuracy of the system.

Being part of the ESA PROBA (PRoject for On-Board Autonomy) programme, a special attention is put on the autonomy of the system. The system should be able to perform autonomously up to 8 orbits, with only high level orders sent every week.

The Formation Flying Software, presented in this paper, is the part in charge of commanding the spacecraft for realizing the mission, while answering the autonomy constraints. This paper describes the architecture of the Formation Flying Software along with its various elements, and presents its implementation in the simulator, along with tests results.

2. General architecture

The Formation Flying Software is part of the Formation Flying System, along with interfaces with the on-board computer. This software is developed by GMV as prime, with SENER and NGC as subcontractors. It is in charge of scheduling, acquiring, maintaining and modifying the relative position and attitude of the spacecraft in the formation. Given the distribution of the manoeuvres to be executed, sensors and actuators, the functionalities for the CSC and the OSC are different and complementary. In terms of hardware, the CSC contains the fine metrology and broad thrusters and the

OSC the fine actuators. In terms of software also, the GNC functionalities have been split into the SC-GNC, responsible for absolute estimation and common to both spacecraft, and the FF-GNC, responsible for relative estimation and control, that presents some differences between the OSC and the CSC.

The Formation Flying Software has been divided into Formation Flying Level Software (FFLSW containing FF-FDIR, FFM, FF-GNC), Spacecraft GNC (SC-GNC) and Actuator Manager (ACT-MNG):

- FF-FDIR (developed by SENER): It is the part of the FDIR dedicated to the formation; it monitors flags and resolves the formation related problems, such as timeouts, collision risks…
- FFM (developed by GMV): The Formation Flying Manager is in charge of providing orders to the rest of the Formation Flying Software to fulfil the mission and monitoring their execution. It is also the module responsible for the autonomy of the system. The FFM interprets the high level commands from ground and derives the formation level timeline of activities. It issues commands to the FF-GNC and the SC-GNC in both spacecraft. FF-FDIR acts in an independent way. In nominal operations the FFM in the OSC takes the lead.
- FF-GNC (developed by GMV for Guidance and Navigation and SENER for Control): It is in charge of estimating the formation relative state vector (Navigation), computing the desired profile and the manoeuvres needed to follow this profile (Guidance), and computing the manoeuvres (Control) related to the formation. The FF-Navigation receives the sensor measurements (from the companion via Inter-Satellite Link (ISL)) and estimates the relative state (position, velocity and attitude) of the formation. Measurements are synchronised and filtered when available, taking into account which spacecraft is the passive one in each part of the orbit as well as the actuations and attitude of each SC. The relative state solution is synchronised with the current time (taking into account the delays between SC and ISL delay). The FF-Guidance computes, on-board the OSC, the impulsive manoeuvres to be executed by the CSC for perigee pass and parking (sent via ISL to the CSC) as well as the target position for formation acquisition and the profiles for formation maintenance and formation manoeuvres to be followed by the FF-Control and SC-GNC. The FF-Control is only present on OSC. It computes the control actions to acquire and maintain the formation, and performs formation manoeuvres using the cold gas thrusters. It also provides manoeuvre control for off nominal situations like CAM and going to safe orbit with cold gas.
- SC-GNC (developed by NGC): It is responsible for estimating the absolute state and attitude of each spacecraft, computing and monitoring the manoeuvres related to the spacecraft.
- Actuator Manager (ACT-MNG (developed by NGC): It prepares the actuations of the thrusters and reaction wheels combining manoeuvres coming from both the FF and the SC GNC.

The functional architecture of both spacecraft is shown on Fig. 2 below.

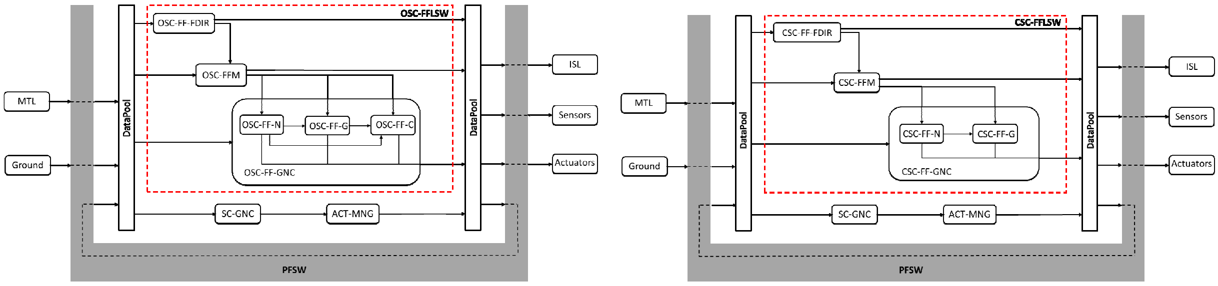

Figure 2. OSC (left) and CSC (right) functional architecture

3. FFLSW

The Formation Flying Level Software (FFLSW) is the one in charge of managing and controlling the formation, including the autonomy level of the system. The main elements are the FF-FDIR, FFM and FF-GNC, which is composed of the FF-Navigation, FF-Guidance and FF-Control.

3.1 FF-FDIR

FF-FDIR of PROBA-3 is the system responsible for ensuring the formation safety during the mission. For this, the FF-FDIR has not only to check the formation status and perform the actions to prevent loss of the mission, but also check the status of the FFS system in charge of the position control on the spacecraft. FF-FDIR is a part of the overall FDIR system in PROBA-3. Complementing FF-FDIR, SC-FDIR is in charge of the failures at Attitude Determination and control System level and it is always active, both in Formation Flying manoeuvres and in stand-alone configuration.
FF-FDIR prototype is not available at the current stage of the PROBA-3 program. It has been scheduled to be fully validated by the following phase and fully integrated in FFS afterwards. In the integrated software at this stage it has been modelled taking into account only representative interfaces to simulate some specific scenarios such as risk of collision. A module part of FF-FDIR has been included that commands to FFM module the execution of a Collision Avoidance Manoeuvre. This command is sent on a time basis, that is, there is not a risk of collision detection module yet available in this prototype,

3.2 FFM

The FFM is the keystone for the autonomy capacity of the mission. It autonomously commands and monitors the execution of the actions for acquiring, maintaining and changing the different formation configurations to fulfil the mission. Two levels have been considered in the FFM. At high level, the timeline ground commands along with on-board parameters are used to elaborate the sequence of FFM modes. At low level, an event list (tasks and conditions) related to the current FFM mode is followed in order to monitor and create the commands to the spacecraft. This separation in high level and low level commands also allows commanding directly the formation from ground, as it can be needed in some cases.
The FFM implements the following functions:

- reorganizing inputs.

- handling the interface with ground via telecommands (both high-level for timelines and low-level for commands)
- checking the FF-GNC mode transition and selecting the new FF-GNC mode that has to be used (and subsequently the corresponding list of events –tasks and conditions- that has to be commanded and checked)
- managing the loaded event list associated with the active FF-GNC mode by checking the conditions and performing the tasks described in the mode.
- preparing outputs, requests and commands to be provided to the rest of the system.

3.3 FF-Navigation

The Formation Flying Navigation (FF-N) processes absolute navigation and attitude data from the SC-GNC, and relative position sensor information, to perform estimation of the relative position and velocity of the spacecraft.

The main challenges of the FF-N are the synchronization and processing of measurements from a high number of sources, with different levels of accuracy, misalignment, bias and latencies, and whose availability varies with flight phase; the processing of these measurements concurrently in two spacecraft that communicate through an Inter-Satellite Link (ISL) which introduces significant latency; and their filtering in a local reference frame, through a model of natural and forced relative dynamics in a highly elliptical orbit.

The design of the FF-N is based on an Extended Kalman Filter (EKF) running at a correction step to update state estimates at an adjusted measurement time. The propagation makes use of relative dynamics models and knowledge of actuation (pre-synchronized to the EKF step). To perform the correction, the measurement matrix is built based on synchronized attitude and relative position estimates. The propagation is based on the equations that model relative motion in elliptical orbit around an unactuated target. To build these equations the orbital elements of the unactuated spacecraft (CSC except during thrusters actuation) are synchronized (through Keplerian propagation) to the propagation time step. The EKF estimates relative position, velocity and covariance in the Local Vertical Local Horizontal (LVLH) frame. The solution is then propagated to local On-Board Time (OBT) using relative dynamics knowledge, together with actuation knowledge from OSC; and CSC actuation management and/or CSC thrusters actuation prediction from FF Guidance.

The architecture of the OSC FF-N is presented on Fig. 3 below.

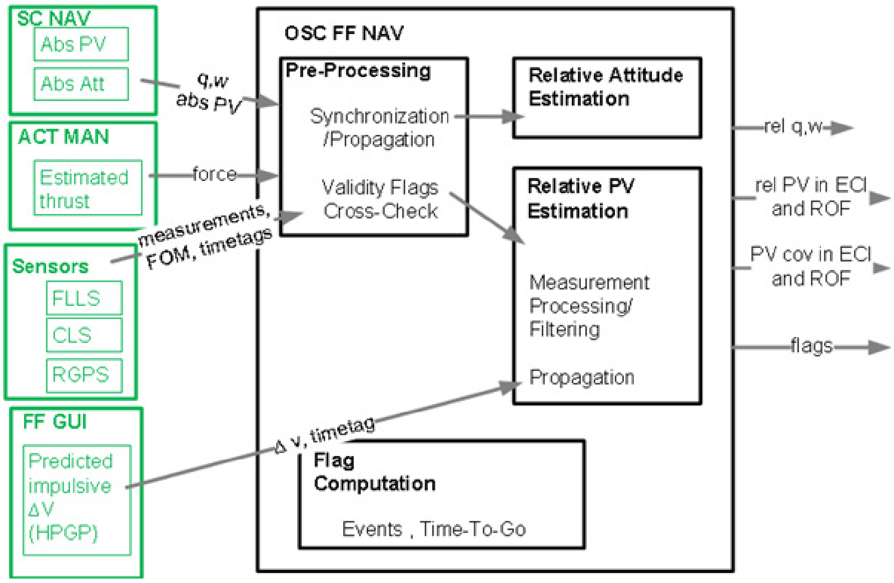

Figure 3. OSC FF-N architecture

3.4 FF-Guidance

The FF-G, taking as input the estimated relative state and orders from the FFM, computes both the impulsive manoeuvres and the forced motion profiles needed during the mission for following the nominal orbit, FF experiments, parking orbit, safe orbit or CAM.

In nominal orbit, three impulsive manoeuvres are required to perform the perigee pass:

- the Direct Transfer Manoeuver (DTM1), computed 3 hours after apogee as a two points transfer, and performed by the broad thrusters (on CSC). It ends the apogee arc.
- the cold-gas correction manoeuvre, computed just after the application of DTM1 also as a two points transfer, and executed by the fine thrusters (on OSC). It corrects the errors introduced by the broad thrusters.
- the DTM2 at the end of the perigee pass, computed as the second manoeuvre of the two points transfer, and executed by the broad thrusters. It starts the formation reacquisition.

In the apogee part of the orbit, in nominal orbit, the FF-G computes the spacecraft relative state that has to be acquired (formation reacquisition) or maintained (station keeping).

Other FF experiments include formation resizing or retargeting. Here too, the FF-G provides a profile to follow for the relative state. In addition, the FF-G computes a profile in attitude.

The parking orbit is a non-drifting orbit that requires a low ΔV to be maintained, and aligns the formation with the Sun at apogee. The FF-G computes the two points transfer manoeuvre to go from nominal to parking. While in parking orbit, the FF-G computes the correction manoeuvres, performed at true anomalies of 90º and 180º. The transfer back to nominal orbit is performed thanks to a single impulse at apogee.

The CAM guidance provides a CAM ΔV that stops the current motion, and adds an escape ΔV.

3.5 FF-Control

The FF-Control (FF-C) is in charge of computing the control force needed to perform formation acquisition, maintenance and to perform orbit manoeuvres with Cold Gas Thrusters (CGT) in OSC. FF-C is composed of three independent sub-modules, implementing each the functionality required in different FFS submodes:

- High Performance Control
- Coarse Acquisition Control
- Impulsive Manoeuvre Control

The High Performance Control covers the experiments of station keeping and of fine formation reconfiguration, maintaining the fine formation during the experiments in the apogee arc. The controller implemented in this module is designed to reduce the relative position error from the range of 1 cm to sub-millimetre level and it results from a process of $H\infty$ synthesis. It is implemented in the discrete state space, sampled at 1Hz, consistent with the very low dynamics of PROBA-3 near apogee. The in-plane MIMO controller (X-Z plane) is separated in this prototype from the out-of-plane SISO controller (Y-axis). A feed-forward force term is added to compensate systematic known effects, such as gravity gradient generated in the FF-Guidance module.

The Coarse Acquisition Control is formulated as a PD feedback controller in charge of acquiring the formation after each perigee pass. The initial error to be corrected is of the order of 5m, and the controller brings the formation down to 1cm accuracy. The proportional and derivative controller gains are scaled with the spacecraft mass to ensure the same dynamical response while the mass decreases due to fuel consumption. This controller also presents some non-linear terms, such as a saturation block to limit the velocity with which the error signal goes towards zero, and a dead-band block to impose a controller limit cycle around zero when the error signal has reached its desired value to avoid spending propellant if the precision is not needed.

The Impulse Manoeuvre Control manages the execution by the OSC of significant impulsive manoeuvres, such as the orbit correction manoeuvres or the CAM. It receives the ΔV command from FF-G and converts them into force commands for the actuator manager. Since the execution of a single command can take several cycles to finish, a feedback is taken from the actuator manager to check how much of the ΔV manoeuvre has taken place and how much remains to be done. When a new command is detected, it is added to the on-going command being executed. If this block is not reset, it outputs the vectorial sum of all the detected commands.

4. SC-GNC and ACT-MNG

4.1 Overview

The SC-GNC performs the tasks of absolute attitude control, angular momentum management, delta-V execution in a dedicated mode and absolute orbit navigation. The SC-GNC is the same for both spacecraft, except for the ACT-MNG subsystem due to the difference of thrusters. The SC-GNC has different modes of operation, depending on the orbital conditions, the units availability and the formation needs, that activate the appropriate GNC functions.

It is subdivided into 4 modules: SC Navigation (SC-N), SC Guidance (SC-G), SC Control (SC-C) and Actuator Manager (ACT-MNG). The SC-N consists in the determination of the current dynamical state (orbit, attitude, internal moving parts) of the spacecraft from measurements, the computation of ephemerides, and the determination and management of on-board time. The SC-G consists in the computation of the desired or commanded dynamical absolute state of the spacecraft and the computation of the difference between the desired dynamical state and the current dynamical state. The SC-C consists in the determination and execution of the necessary control commands that will bring the current dynamical state of the spacecraft coincident with the desired state in a stable and accurate way. The ACT-MNG post-processes both FF-GNC and SC-GNC commands to allow the actuators to execute them.

4.2 Implementation

The SC-GNC SoftWare (SW) is dedicated to implement the GNC functions as well as the actuators management for the stand-alone spacecraft: CSC, OSC and Stack, in eight SC-GNC modes: Stand-By Mode, Sun Acquisition Mode in Stack configuration, Inertial Attitude Mode in Stack configuration, Sun Acquisition, Orbit Control Mode, Inertial Attitude, Target Pointing, Thruster Based Inertial Mode.

The architecture of the SC-GNC SW is hierarchic. The SC-GNC SW is composed of modules of different levels: from level-0 to level-2. The high-level architecture of the SC-GNC is presented in Fig. 4.
The SHELL, at level-(-1), includes all elements of the SW (level-0 and lower), namely GNC and MNG. The GNC, at level-0, includes all elements of the GNC SW (level-1 and lower) that are NAV, GDC and CTL, at level-1, each of them including respectively the navigation, guidance and control functions of level-2 or lower. The MNG, at level-0, includes all elements of actuator management.

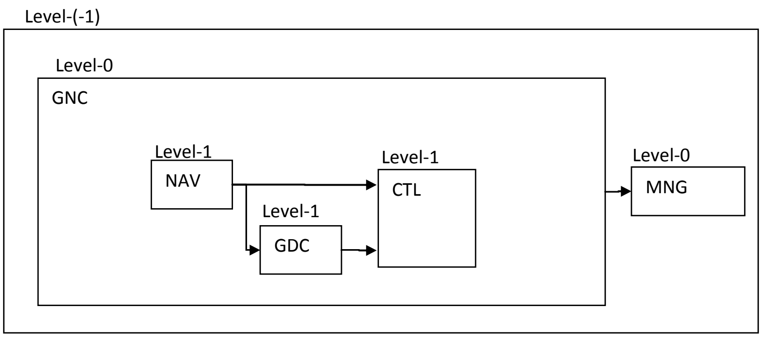

Figure 4. LEVEL-1 Function Breakdown

4.3 Performances

The SC-GNC SW functionality and performance have been assessed by means of simulation-based tests. These tests, performed in a dedicated simulator, have been carried out in order to show the functionality of the SC-GNC SW algorithm, characterise their performance and characterise the critical contributors to the pointing budget.

Sensitivity analysis has been performed in order to define the impact to each contributor to the pointing budget. The budget results to the performance summarised in Tab. 2 that compares the pointing budget results and the requirements.

Table 2. Requirement Versus Performance from Pointing Budget

CSC			X-Axis Around LOS		Y-axis		Z-axis	
			Requirement	Performance	Requirement	Performance	Requirement	Performance
HPAP	CTL	AAE	300 arcsec (TBC) (1σ)	3.03	2.8 arcsec (TBC) (1σ)	3.56	2.8 arcsec (TBC) (1σ)	2.95
		AAS	30 arcsec over 10 seconds (TBC) (1σ)	0.5	0.88 arcsec over 10 seconds (TBC) (1σ)	0.68	0.88 arcsec over 10 seconds (TBC) (1σ)	0.54
	NAV	AAME	30 arcsec (TBC) (1σ)	1.3	1.25 arcsec (TBC) (1σ)	1.32	1.25 arcsec (TBC) (1σ)	1.33
		AAMS	0.75 (TBC) arcsec (1σ), over 4hr	0.4	0.75 (TBC) arcsec (1σ), over 4 hr	0.43	0.75 (TBC) arcsec (1σ), over 4hr	0.48

OSC			X-Axis Around LOS		Y-axis		Z-axis	
			Requirement	Performance	Requirement	Performance	Requirement	Performance
HPAP	CTL	AAE	900 arcsec (TBC) (1σ)	14.99	30 arcsec (TBC) (1σ)	15.64	30 arcsec (TBC) (1σ)	11.14
		AAS	N/A		N/A		N/A	
	NAV	AAME	300 arcsec (TBC) (1σ)	2.37	5 arcsec (TBC) (1σ)	1.97	5 arcsec (TBC) (1σ)	1.6
		AAMS	TBC arcsec (1σ)		TBC arcsec (1σ)		TBC arcsec (1σ)	

This table shows that some performance objectives are not fulfilled for CSC:
AAME results along Y and Z axes are slightly beyond the performance objective (1.33 arcsec while 1.25 arcsec is targeted) this error is dominated by the contribution of the star trackers bias (1.15 arcsec).
AAE results along Y and Z axes are also slightly beyond the performance objective (3.56 arcsec and 2.95 arcsec respectively while 2.8 arcsec is targeted). AAE and AAS are dominated by the actuator noise for which the contribution to AAE and AAS has been evaluated to 1.73 arcsec. Indeed, while CSC SC-GNC SW algorithms allow fine and strongly stable pointing (0.08 arcsec 1 sigma when: the knowledge of the spacecraft is perfect (no misalignment), the actuator noises are neglected and the star tracker noise is considered) the reaction wheels prevents producing the control action required for fine control: the noise is larger than the requested signal for accurate control.
Thus, the tests have demonstrated that SC-GNC SW is operational despite the fact that for CSC, current performance requirements are not compatible with the reaction wheels noise. This problem is managed at the actuator unit level.

5. Integration process

The software is developed in GNCDE framework (GMV development environment for space missions GNC in Matlab/Simulink). It allows an easy management of the parameters initialization and output, the possibility to use the integrated library in the Simulink model assembly and to take advantage of several integrated tools for performing analysis on the prototype. In order to develop the Formation Flying System, a complete Functional Engineering Simulators (FES) has been developed within GNCDE. It is composed by:

- Real World: containing the ephemeris, the sensors, actuators, power system and DKE for each spacecraft
- Ground Segment: simulating ground orders to the spacecraft
- CSC_OBC: the on-board computer of the CSC, containing the CSC Formation Flying Software, along with the Platform Software emulator
- OSC_OBC: the on-board computer of the OSC, containing the OSC Formation Flying Software, along with the Platform Software emulator

Two implementations very similar of the Formation Flying Software are present on the CSC OBC and the OSC OBC. They reflect the architecture described in Section 2. Due to strong requirements on the attitude of the spacecraft, the SC-GNC runs at 4Hz, while the other modules (FF-GNC, FFM, FF-FDIR) run at 1Hz.

In order to fasten the development of the FFLSW, a simplified version of the FES has been created, with the same interfaces that does not consider actuators, absolute sensors, power issues and emulates the SC-GNC. Once a stable version of the FFLSW has been achieved on this FES, it has been integrated into the complete FES with the SC-GNC. All the models have been implemented using Simulink blocks, embedded Matlab functions or Stateflow.

Thanks to the definition and application of coding rules during the whole process of implementation in Matlab, the Formation Flying Software can be automatically translated into C using autocoding techniques. In parallel, the real world has been autocoded in SMP2 and integrated in the Software Based Test Bench (SBTB developed by Spacebel, real time validation facility for the FFSW). Finally the FFSW C-code has been encapsulated in a behavioural code of the platform software and tested in the SBTB. This step is performed for any version of the code validated in the FES (even without the final version of the platform software), in order to detect and correct possible problems at the earliest moment.

6. Tests

The tests results presented here correspond to the PDR tests performed with the complete FES in Matlab/Simulink. They aim at demonstrating that the Formation Flying Software fulfils the requirements for representative scenarios. There are 6 selected scenarios, as described in Tab. 3 below:

Table 3. Description of the PDR tests

Test	Title	Description
Test 1	Multiple Nominal Orbit	Covers 3 nominal orbits. Demonstrates the integration of the software, the stability of the modules.
Test 2	Parking Orbit	Several orbits. Covers Parking Acquisition, Maintenance and Return to Nominal. Demonstrates each of these manoeuvres.
Test 3	CAM	Demonstrates the CAM computation and application.
Test 4	Deployment	Demonstrates the dynamics of the two satellites after deployment through to Commissioning Orbit acquisition and its safety.

Test 5	Nominal Orbit fully instrumented	One orbit. Evaluates the performances of the system in a nominal orbit.
Test 6	Safe Orbit	Demonstrate the dynamics of the two satellites during the Safe Orbit, and the possibility to reacquire correctly the Nominal Orbit afterwards.

The results coming from the Test 5 are presented in this paper, since they show the most representative nominal orbit, and they allow a primary evaluation of the performances of the system.

This test is performed over one nominal orbit. The simulation starts in apogee, with the spacecraft in formation, and the acquisition of the optical sensor. After 3 hours, the DTM1 is computed, and then performed. Afterwards, a correction manoeuvre is computed and performed with the milli-newton thrusters. The spacecraft are then in free flight during the perigee pass phase, where the GPS is available one hour around perigee. At the end of the perigee pass, the spacecraft (namely CSC) is braked. The optical sensors and the formation are acquired and maintained, allowing performing coronagraphy during the 6 hours of the apogee phase. All the outputs of the FF-GNC, sensors, SC-GNC are stored, and processed afterwards in order to obtain an evaluation of the performances. The results are shown in Fig. 5 to Fig. 8 below.

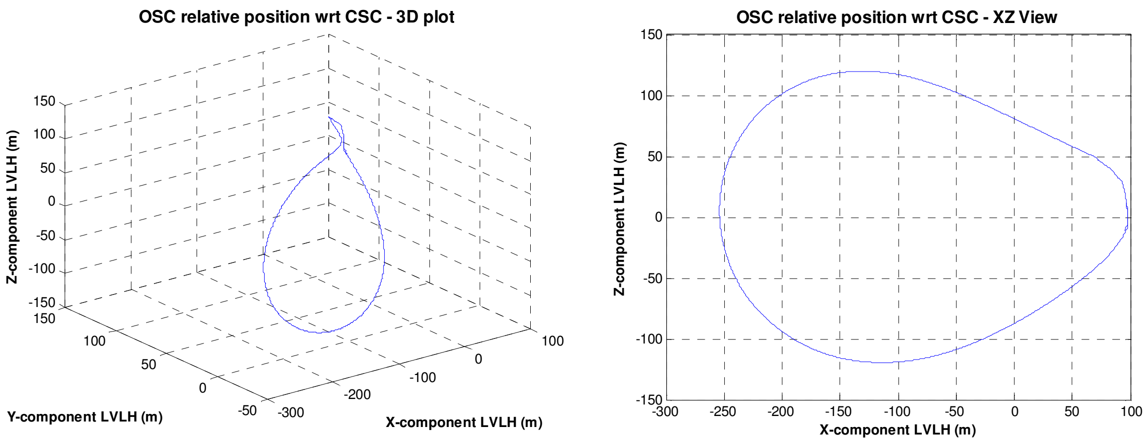

Figure 5. Relative trajectory during the Nominal Orbit

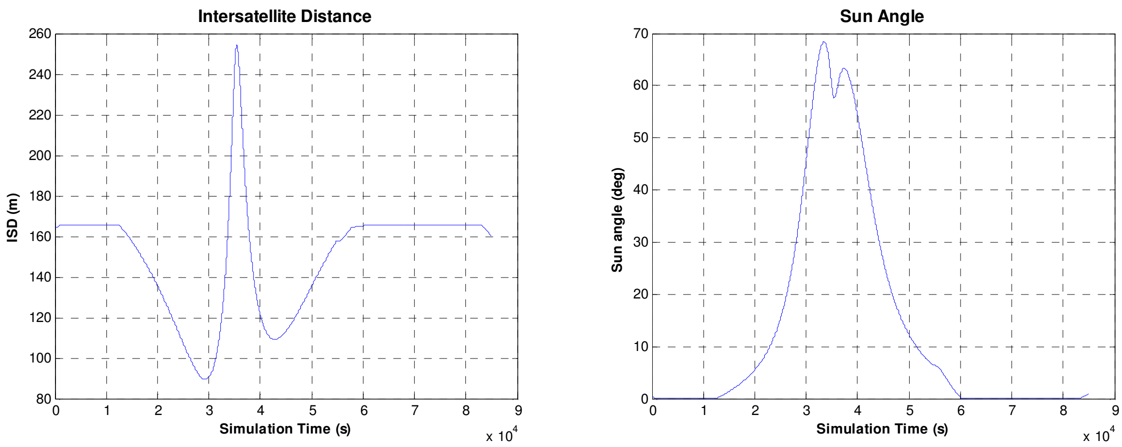

Figure 6. Intersatellite distance and Sun angle during the Nominal Orbit

As can be seen in the parts where Formation Flying is performed (from t=1000 t=12000 and t=60000 to t=84000 aprox.), the ISD stays at a controlled value, around 160m, and the angle of the formation with respect to the sun stays close to zero.

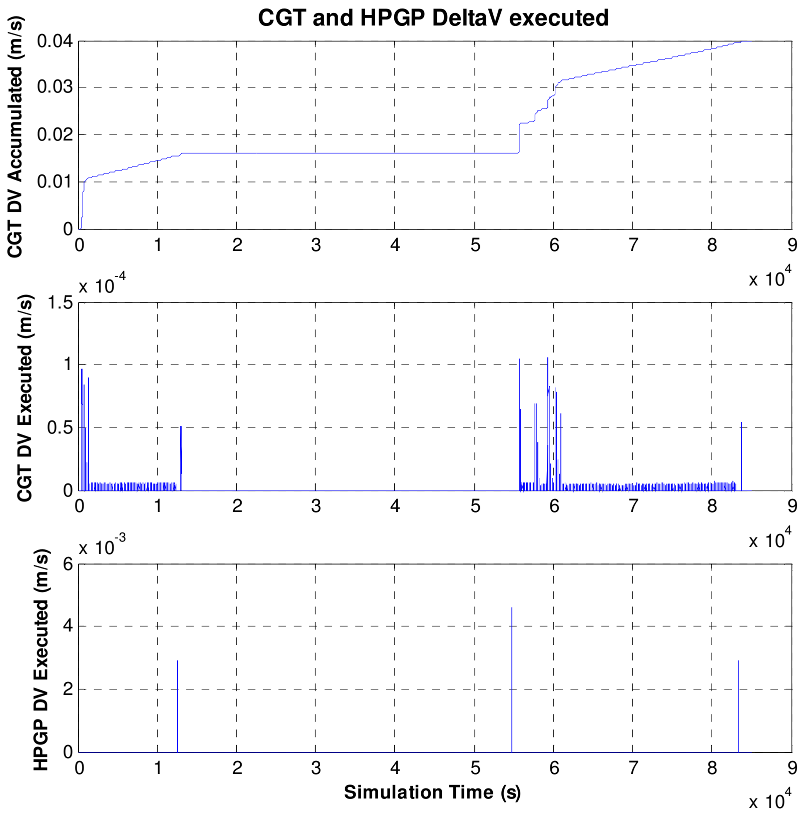

Figure 7. Thrusters actuations during the Nominal Orbit

In the figure above it can be clearly observed the impulsive manoeuvres performed with the HPGP thrusters to perform the perigee pass as well as the CGT actuation for formation acquisition and maintenance.

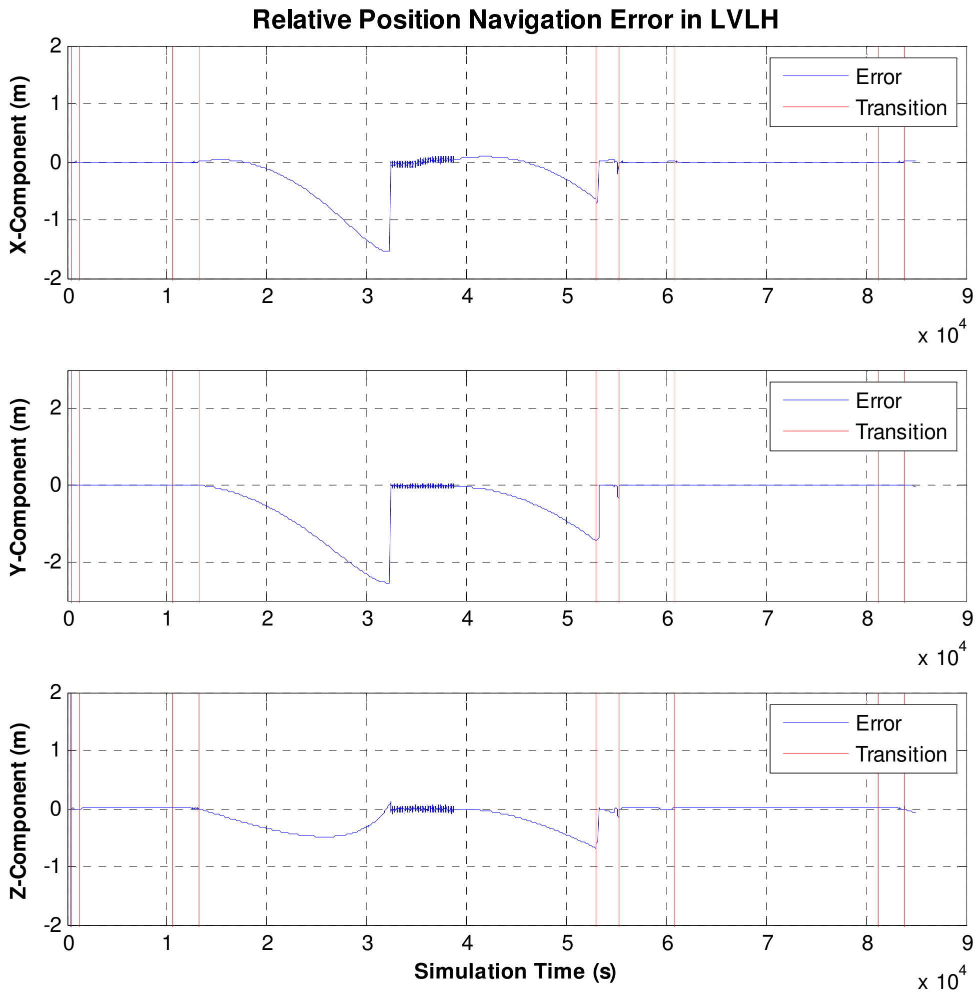

Figure 8. Navigation error during the Nominal Orbit

The figure above shows the error in relative position between the output of the FF-NAV and the real world values. During Formation Flying phases, this error is very low. It can be noted the presence of GPS data around apogee.

The summary of the performances, in terms of error and stability of position and attitude, are presented in Tab. 5.

Table 5. Position and Attitude performances of the Test 5

SC	Type	Error	xyz	HPAP Value (req)	Unit	Remarks
CSC	CONTROL	AAE	yz	0,08 ± 3,08	arcsec	All ISD
			x	2,08 ± 2,31	arcsec	All ISD
		AAS	yz	0,0004 ± 0,63	arcsec	All ISD, over 10 sec
			x	0,0001 ± 0,42	arcsec	All ISD , over 10 sec
	MEAS.	AAME	yz	0,05 ± 0,57	arcsec	All ISD
			x	2,04 ± 0,48	arcsec	All ISD
		AAMS	xyz	0,03 ± 0,58	arcsec	over 4h in post-pro
OSC	CONTROL	AAE	yz	0,47 ± 8,72	arcsec	All ISD
			x	1,67 ± 8,29	arcsec	All ISD
	MEAS.	AAME	yz	0,02 ± 1,62	arcsec	All ISD
			x	2,02 ± 1,38	arcsec	All ISD
Formation	CONTROL	RDE	yz	1,05 ± 0,14	mm	ISD <160m
			x	0,16 ± 0.20	mm	All ISD
	MEAS.	RDMS	yz	0,039 ± 0,11	mm	over 4h in post-pro
			x	0,006 ± 0,02	-	-

The objective of the test campaign at this stage was not to validate the performances of the system but to verify the functionality of the integrated system. Nevertheless the performances have been analysed and potential problems identified. Most of the performances are already met by the system at this stage.

As already explained in section 4.3, the attitude errors are mainly dominated by the star tracker bias and the actuator noise at this stage. While in the case of the relative position error, the main source is residual error after structural calibration (FLLS location error of 1mm). These problems are to be analysed and solved during the next phase. In particular, the calibration procedures and expected performances will have to be consolidated.

At the end of the prototyping phase, the automatically generated C-code for the Formation Flying SW was run on the real-time validation facility (SBTB). It provided statistics on the CPU usage, and checked that the code does not generate overruns conditions (missed deadlines for cyclic tasks) neither floating point exceptions (overflow, division by zero…). All the results were compared with the Simulink outputs, concluding that the Formation Flying SW outputs map the Simulink reference data with high precision for the reference mission.

Furthermore, the Formation Flying SW CPU usage has been measured for the nominal scenario (time consumed by the Formation Flying Software on the target Leon2 processor similar to the one on-board of the PROBA-3 mission). Concerning the Coronagraph SC, the Formation Flying SW CPU usage remains stable around 8%, while on the Occulter SC the CPU usage is between 8 and 9.5%. This means that the algorithms have been correctly prototyped and optimized taking into account the real-time execution constrains, achieving a CPU usage very stable, under control and relatively low at this stage, and leaving a high margin for Formation Flying algorithm and

SW upgrades or the inclusion of more demanding algorithms (relative GPS navigation algorithms, experiments, …).

7. Conclusion

PROBA-3 is one of the first missions to integrate both the Formation Flying and autonomy concepts. In both fields, the objectives to be demonstrated are very ambitious: achieve a millimetre precision for the formation at 150m during apogee, and realize the mission with only a few high level commands once a week.
The mission, in which take part several companies from Spain, Belgium, Canada, has successfully passed the Preliminary Design Review, closing the Phase B2. The completion with success of the PDR demonstrates that the approach followed for the integration of the software, made by many teams in several companies, is the correct one. Phase C will start in the next months and allow to refine the software presented in this paper. The Formation Flying Software of PROBA-3 may become a reference for the future Formation Flying missions.

8. References

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