DESIGN OF IDENTIFICATION AND COMPENSATION METHODS FOR SPACE RIDER GNC ALGORITHMS

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ABSTRACT

The ESA Space Rider System is designed to provide Europe with the first reusable and independent end-to-end orbital platform, to deliver an uncrewed orbital laboratory able to de-orbit, re-enter, land and be relaunched after limited refurbishment. High versatility and reliability are thus requested for the AOM since the Space Rider mission foresees various in-orbit experiments, ranging from payload for commercial and institutional applications to IOV/IOD missions, microgravity experiments, and Earth/Space observation. From this perspective, it becomes of paramount importance to manage all the operative conditions for which the GNC must guarantee the best performance in terms of accuracy and operative duration. Attitude sensors must guarantee high data reliability despite being subjected to stresses during launch, a harsh operating environment and any assembly errors during integration. Constant in-orbit calibration is, therefore, necessary to meet requirements. Actuators, on the other hand, must be able to compensate for system and external uncertainties and manage any non-nominal condition. This paper aims at presenting how a class of non-linear filters, called Sliding Mode Filters, can be applied to identify and eventually compensate for different sources of parasitic errors inside the GNC loop. The performance of this approach is also shown wrt other classic techniques, and the suitability of the real-time implementation inside the Flight Software is shown in terms of possible improvements.

1 INTRODUCTION

The ESA Space Rider System (SRS) is an uncrewed orbital platform able to de-orbit, re-enter, land and be relaunched after limited refurbishment. It will be the first European reusable and independent end-to-end space transportation system for Low Earth Orbit (LEO), which will commercialise a novel service for various commercial and institutional space and non-space applications, performing a wide variety of experiments in microgravity, In-Orbit Demonstration/Validation missions for Earth observation, science and robotic exploration. The great potential lies in being able to transport experiments back to Earth once the mission is complete. SRS developed from the accumulated experience of Intermediate eXperimental Vehicle (IXV). The IXV was the first European vehicle to successfully perform an autonomous re-entry from LEO. IXV was a cornerstone mission, which opened the door to a wide range of possible manned or reusable unmanned missions from terrestrial orbits and beyond, which have to deal with hypersonic flight conditions. In order to be able to perform a wide range of

Figure 1: Space Rider System

experiments for a broad clientele, SRS has demanding pointing requirements for the orbital phase, regarding both attitude determination (accuracy of $0.03°$) and control (accuracy of $0.04°$), which result in an overall required pointing accuracy of $0.05°$ on each body-axis. Moreover, SRS has to be able to compensate for any failures in a timely manner, to make the most of the two months' mission. This work arose from the necessity to guarantee the fulfilment of these requirements even under off-nominal conditions in which both actuators and attitude sensors might operate. Specifically, it will be addressed in-orbit Star Tracker (STR) misalignments, using Sliding Mode Observers (SMO) as in [1]–[3] and compensation techniques, and Reaction Wheels (RWs) degraded conditions, using a Sliding Mode Estimator and an adaptive Fault Tolerant Control (FTC) for optimal torque allocation as described in [4]. The main contribution brought by this thesis work concerns the robustness of the proposed methods, which do not merely identify non-nominal behaviour, but estimate their magnitude with non-linear estimators and propose dedicated real-time compensations.
The paper is organized as follows. In Section 2 SRS and the mission are described. In section 3 the AOM GNC is described in detail and its issues are addressed. In section 4 identification and compensation methods are explained. Then in Section 5 simulation results are shown. Finally, in Section 6 conclusions are outlined.

2 SPACE RIDER SYSTEMS AND MISSION DESCRIPTION

The Space Rider System (Figure 1) is composed of two different modules, which have different functionalities. The AVUM Orbital Module (AOM) is a modified version of the Vega-C upper stage, as described in [5]: it supplies power to the whole system, and it handles telemetry data, proving as well thermal, attitude and orbit control. The module has a bi-propellant main propulsion for the initial orbital injection and for the de-orbiting manoeuvre, as well as a mono-propellant secondary propulsion (RACS) for roll and attitude control. AOM is actuated through 4 RWs in a Symmetric Pyramid configuration and 3 magnetorquers (MTQs), and it is equipped with two STRs, one IMU (Accelerometers + Gyroscopes) and a GPS receiver. The AOM is the expendable part of the SRS, and it is supposed to burn in the atmosphere. The Re-entry Module (RM) is the lifting body, it is equipped whit a Multi-Purpose Cargo Bay (MPCB) within which the experiments will return to Earth. Moreover, inside the MPCB is placed an additional STR, of particular interest for this work. The RM is the reusable part of the SRS and it is supposed to carry out at least 6 missions before being decommissioned.
In a typical mission, as shown in Figure 2 and explained in [6], SRS will be launched from Kourou spaceport in French Guyana atop Vega-C. It will be injected in a 400km altitude orbit, and it is designed to operate at different orbital inclinations, from equatorial to SSO, depending on mission objectives. The platform will remain in a low-drag orbit for at least two months performing all scheduled scientific operations. At the end of operations, the AOM will execute a re-entry boost to

Figure 2: Space Rider Mission

de-orbit, before separating from RM. Afterwards, the RM will conduct an autonomous and controlled re-entry in the atmosphere, which will lead to a precise soft landing on the ground, with an estimated landing accuracy of about 150m. Depending on orbital inclinations, the landing site may vary: for low inclination orbit and as well for the maiden flight, the landing site will be Kourou (French Guyana), while Santa Maria (Azores) and Italy are the sites considered for landings from orbits with inclinations $> 37°$. In this way, payloads will be brought back to Earth, giving Europe access to a whole new range of easily accessible and quickly executable in-orbit experiments. The landed RM will be then refurbished and integrated with a new AOM, to be ready to fly again with an estimated turnaround time is about 6 months.

3 SPACE RIDER AOM GNC AND THE ADDRESSED ISSUES

The orbital GNC is the one of interest for this work, and the operational mode considered during analysis is Bay to Nadir/Zenith: it is an attitude-keeping in which the MPCG is directed to Nadir/Zenith and the additional degree of freedom is used to expose the solar array toward the Sun, exploiting as well the Solar Array Drive Mechanism. The attitude control is performed by RWs, and the total pointing accuracy required is $0.05°$ (3σ). Moreover, magnetotorquers are constantly employed for unloading the wheels through a bang-bang logic, thus reducing attitude-keeping interruptions required for desaturation with RACS. SRS 3-axes commanded torque is computed using a PID controller. Allocation to the 4 wheels is not carried out by simply using the assembly matrix Z_w but is subjected to an optimisation that refers to the approach proposed by Yoon [7]. Conventionally, torque optimisation exploits the minimum L_2 norm solution, which simply minimises the square sum of the torques, i.e. the total power required. The L_∞ norm, conversely, minimises the maximum absolute value of the individual torque and thus may be of greater interest for greater agility of the system. The disadvantage lies in the difficulty to express the L_∞ norm solution, for which Yoon exploits symmetries of the pyramid configuration with 4 identical RWs.
The two main issues addressed are strictly related to the above-mentioned conformation of SRS and its mission constraints (section 2). Firstly, due to the significantly distant between the two STRs on

the AOM and the MPCG, their measurements are affected by any structure release in orbit, thermal deformations or launch solicitations, which cause misalignments wrt the expected nominal STR mounting direction. It was therefore necessary to test and validate through analyses a method able to carry out a precise characterisation along the orbit of the misalignments of these two STRs at the beginning of a mission using the third STR in the MPCB, to ensure the reliability of measurements wrt MPCG from all three STRs. Furthermore, in order to make full use of the limited two-month orbital time, a method was implemented to identify and compensate in real-time for any loss of RW efficiency that could arise in orbit. In fact, a large number of malfunctions that RWs can suffer imply in most cases a loss of efficiency of the wheel [8], i.e. a decrease in the reaction torque delivered wrt the commanded one. The two issues were addressed by making use of a complete SRS attitude dynamics simulator, which includes external disturbances, uncertainties on actuators and sensors as declared by manufacturers, uncertainties on models, etc.

4 IDENTIFICATION AND COMPENSATION METHODS

Before specifying the observers implemented and the compensation methods used to address the two issues, an overview of the SMOs is proposed, having made extensive use of them in the prosecution of the work.

4.1 Sliding Mode Observers

The Sliding Mode is a non-linear technique which originated from the theory of Variable Structure Systems, as in [9]. The method has been very successful in controlling problems regarding complex systems subject to uncertainties. The idea behind this is to control the dynamics of a system by injecting a discontinuous input which forces the system to reach the sliding surface in finite time and subsequently stay on it. Sliding Mode Observers still exploit sliding surfaces but for a different purpose: estimating the states of a system using measured input and/or output. They potentially ensure robustness wrt system and external uncertainties and finite time precise estimations. The main drawback of the sliding mode is chattering, which arises as a direct consequence of the discontinuous injection term. An observer consists of a mathematical replica of a system, in which are included inputs and the injection term.
Let's consider the following classical linear system in the matrix form

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) \end{aligned} \tag{1}$$

where $A(t)$ is the state matrix, $B(t)$ is the input matrix, $C(t)$ is the observation matrix, while $x(t)$ represents the state, $u(t)$ is the input while $y(t)$ is the output. In the end, the purpose of the observer is to estimate the state variable $x(t)$ by making use of the information contained in $u(t)$ and $y(t)$. The first-order SMO applied to a first-order linear system has the following form

$$\begin{aligned} \dot{\hat{x}}(t) &= A\hat{x}(t) + Bu(t) + L\nu \\ \hat{y}(t) &= C\hat{x}(t) \end{aligned} \tag{2}$$

where L is a gain matrix to be determined, $\hat{x}(t)$ represents the state estimation, $u(t)$ is the input, $\hat{y}(t)$ is the output estimation and ν is the discontinuous injection term. The simplest way of defining the injection term is

$$\nu = \rho \cdot sgn(e_y(t)) \tag{3}$$

where ρ is a diagonal matrix of constant values and $e_y(t) = \hat{y}(t) - y(t)$. In this case, the injection term ν is chosen with respect to the sliding surface $S = \{e_y(t) =: Ce_y(t) = 0\}$, in order to force

$e_y(t)$ towards S in a finite time and then make it stick on it. To ensure convergence of the SMO, it is necessary to choose properly ρ. Normally, the optimal choice that ensures robustness is made following a study of the conditions under which the system will operate [10].

As mentioned earlier, chattering is in fact one of the main problems affecting SM and SMO. Over the years, numerous methods have been proposed to overcome this problem, and they mainly involve the substitution of the $sgn(e)$ function with other functions that approximate the discontinuity of sgn, when $e \rightarrow 0$, in a smoother way. However, the more the discontinuity is reduced, the more the SM tends to lose rapidity and robustness to parameter uncertainties. Another solution to overcome chattering is to use higher-order SMO. Higher-order SMOs, as in [11], have also the advantage that they can be applied to systems with a relative degree greater than one achieving exact results. This becomes a crucial aspect in dealing with both the attitude and the position dynamics of an orbiting spacecraft. The observer proposed in this work is based on the super-twisting algorithm. In this case, the sliding surface can be defined as $S = \{e : \dot{e} + Ce = 0\}$, where e is the error between the state and the estimation, and the aim is to bring states and state derivatives on it and make them stay there.

Let's consider the following time-varying second-order non-linear system

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f(t, x_1, x_2, u) + d(t) \end{cases} \tag{4}$$

where x_1 and x_2 are the states, specifically a state and its derivative, u the input, $f(t, x_1, x_2, u)$ the non-linear system function and $d(t)$ the unknown but bounded disturbance. Moreover, let's suppose we are able to measure the state x_1 by means of some sensors, and thus have the measurement y_1.

The super-twisting observer applied to the system in (4) has the following form

$$\begin{cases} \dot{\hat{x}}_1 = \hat{x}_2 + \lambda |\widetilde{x}_1|^{1/2} sgn(\widetilde{x}_1) \\ \dot{\hat{x}}_2 = f(t, \hat{x}_1, \hat{x}_2, u) + \alpha \, sgn(\widetilde{x}_1) \end{cases} \tag{5}$$

The new terms $\widetilde{x} = y - \hat{x}$ are the estimation errors, i.e. differences between measurements and state estimations. The super-twisting observer allows for exact results dealing with dynamics of relative degree two, under the convergence conditions reported in [12].

In this overview, the state function of the system reported in (5) is deliberately unspecified, as are the state variables. They will be detailed hereafter by applying SMOs to case studies.

4.2 Star tracker misalignments

To characterise the magnitude of misalignments, it is necessary to compare the corrupted measurement of a STR, in our case the ones on the AOM, with a reference measurement, in our case the one of the STR in the MPCB. Firstly, an observer robust to uncertainties is used in order to obtain two precise estimates that allow us to identify subsequently the magnitude of the misalignment.

The proposed observer derived from the Super-Twisting one presented in equation 5, where non-linear system function $f(t, \hat{x}_1, \hat{x}_2, u)$ is nothing other than the equation of the spacecraft attitude dynamics as in [13], [14]. By adapting the equation to actuators available on SRS (i.e. RWs and MTQs), the observer equations become as follow

$$\begin{cases} \dot{\hat{\boldsymbol{\theta}}} = \hat{\boldsymbol{\omega}}_B + \lambda |\boldsymbol{y} - \hat{\boldsymbol{\theta}}|^{1/2} sgn(\boldsymbol{y} - \hat{\boldsymbol{\theta}}) \\ \dot{\hat{\boldsymbol{\omega}}}_B = -J^{-1}(\hat{\boldsymbol{\omega}}_B \times (J\hat{\boldsymbol{\omega}}_B + \boldsymbol{H}_w) + \boldsymbol{T}_w - \boldsymbol{T}_{ext}) + \alpha \, sgn(\boldsymbol{y} - \hat{\boldsymbol{\theta}}) \end{cases} \tag{6}$$

Specifically, the state variables used are clearly the estimated angular velocity in body frame $\hat{\boldsymbol{\omega}}_B$, and the spacecraft attitude expressed through the Euler's angles parametrization, $\hat{\boldsymbol{\theta}}$. Furthermore, $\boldsymbol{y}$ is the measurement vector coming from STRs, expressed also with Euler's angles.

Once an estimate of the spacecraft attitude with the two STRs has been obtained, the compensation is nothing more than a calculation of the error between the two measurements, and a consequent rotation of the corrupted measurement by an amount equal and opposite to the calculated error. The computations exploit quaternion rotations.

4.3 Reaction Wheel off-nominal behaviours

In order to provide an overview of the logic used to address the issue, a representative block diagram of the logic of the algorithm used is shown in Figure 3.

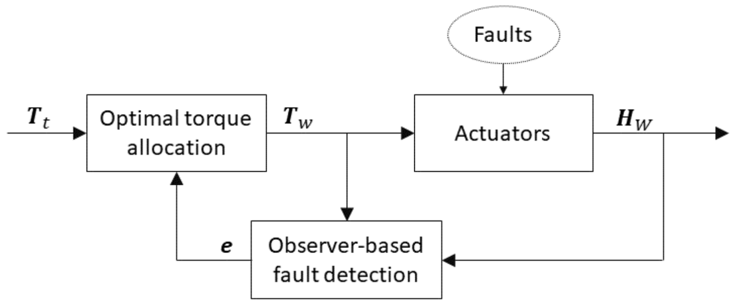


Figure 3: Structure of the RWs applied method

In particular, it represents the portion of the GNC involved in the study. The parameters reported and used in the algorithms are the commanded total control input $\boldsymbol{T}_t \in R^3$ in body-axes, the commanded torque to the 4 wheels $\boldsymbol{T}_w \in R^4$ and the wheels' angular momentum $\boldsymbol{H}_w$, derived directly from tachometer measurements of the angular velocity of the wheels. Moreover, one of the most important parameters of the analysis is the efficiency of the RW, defined as $\boldsymbol{e} = T_{act_i}/T_{cmd_i}$, also expressed as a diagonal matrix $E_w = diag(\boldsymbol{e})$. The logic of the implemented algorithm can be divided into two steps: firstly, it is necessary to identify actuators undergoing an off-nominal functioning. Subsequently, the 3-axes commanded torque is redistributed to the 4 actuators taking into account the faulty ones and aiming to reduce their use.
The identification phase makes use again of a SMO. Starting from the available measurements, i.e. those of the angular momentum of the wheels $\boldsymbol{H}_{w_{meas}}$, the aim is to estimate the torque produced by the RWs. The observer proposed is the one described in [15] for second-order dynamic systems ($\ddot{x}_1 = f$), when only a single measurement is available to the system (y_1):

$$\begin{cases} \dot{\hat{\boldsymbol{x}}}_1 = \hat{\boldsymbol{x}}_2 + k_1 sgn(\boldsymbol{H}_{w_{meas}} - \hat{\boldsymbol{x}}_1) \\ \dot{\hat{\boldsymbol{x}}}_2 = k_2 sgn(\boldsymbol{H}_{w_{meas}} - \hat{\boldsymbol{x}}_1) \end{cases} \tag{7}$$

For ease of writing, the parameters used are $\hat{\boldsymbol{x}}_1 = \hat{\boldsymbol{H}}_w$, the estimation of the wheels angular momentum, and $\hat{\boldsymbol{x}}_2 = \dot{\hat{\boldsymbol{H}}}_w$, the estimation of the derivative of wheels angular momentum. With this variable choice, it is possible to obtain a set of state estimates which are less prone to fluctuation following a more linear evolution if compared to torques and their derivations. To define the wheel efficiency parameter $\boldsymbol{e}$ in a meaningful way, it is necessary to make some considerations about how the commanded torque changes due to the real effects of the RW equipment. It is of utmost importance to determine in orbit and during analysis whether the discrepancy results from known and expected effects of RWs or whether they are indices of malfunctioning, and this is done by means of actuator models.
The commanded 3-axes torque coming from the controller has to be redistributed to actuators taking into account estimated faults ($\boldsymbol{e}$), by means of a reconfiguration closed-loop routine, which is external

to the controller (i.e. it does not need to be reconfigured if efficiency decreases are identified). It is known that the commanded torque of every wheel can be expressed as $\boldsymbol{T}_w = Z_w^{\dagger}\boldsymbol{T}_t$, where $Z_w^{\dagger}$ is the pseudo-inverse matrix of the mounting matrix Z_w, which satisfies the equality $Z_w Z_w^{\dagger} = I_3$. The choice of $Z_w^{\dagger}$ is therefore not unique, and it can be selected in several ways. The choice was made in order to minimise at each step the following minimisation problem

$$\min_{\boldsymbol{T}_w}(\boldsymbol{T}_w^T E_w^{-1}\boldsymbol{T}_w) \text{ subject to } \boldsymbol{T}_t = Z_w\boldsymbol{T}_w \tag{8}$$

which aims to minimise the sum of squares cost related to the RWs commanded torque $\boldsymbol{T}_w$, weighted by E_w, as proposed in [4]. The optimal solution to the problem is given by

$$Z_w^{\dagger} = E_w Z_w^T (Z_w E_w Z_w^T)^{-1} \tag{9}$$

When a loss of efficiency occurs, E_w is no more equal to the identity matrix, and so the control effort is reallocated trying to minimise the use of the faulty actuator, which is also more prone to unexpected and potentially harmful behaviour since it does not function nominally. At each step, the pseudo-inverse matrix $Z_w^{\dagger}$ is calculated, and T_t is redistributed without the necessity to redesign the controller. In a fault-free condition, when the weighting matrix is equal to the identity matrix I, the $Z_w^{\dagger}$ matrix results to be the classical Moore-Penrose pseudo-inverse. As a final step, each RW commanded torque T_{w_i} is rescaled by a factor $1/e_i$, to minimise the mismatch between commanded and actuated torque. This action, being carried out after the controller, makes it possible to obtain an actuated torque similar to that commanded one, thus minimising the discrepancy and consequently not having unexpected system behaviour.

5 SIMULATION RESULTS

The two GNC problematics introduced and explained in the previous chapters are addressed separately, making use of the same simulator implemented in MATLAB & Simulink environment. Simulations reproduce a B2N attitude keeping, in a 400km circular orbit.

5.1 Star Tracker misalignments

STR misalignment can be represented as consisting of two main contributions, a constant misalignment due to mounting errors, zero-g release, vibrations, etc., and a variable misalignment along the orbit, mainly caused by thermo-elastic deformations given by transitions between eclipse and non-eclipse conditions. The magnitude of these misalignments came from thermo-structural studies, to be confirmed once in orbit. Figure 4 shows the misalignment along the orbit imposed on the STR support, expressed in the STR local reference frame.
Simulations compare an Extended Kalman Filter (EKF) based observer with the SMO previously proposed (section 4.2). The equations used for the EKF are the classical ones for application to attitude dynamics, not reported as they are beyond the scope of this work. A complete description can be found in [16]. It is initially shown in Figure 5a the error in attitude estimation wrt true state of the STR subject to misalignment. In this instance, no correction method is applied. The black line indicates SRS attitude determination error requirement ($0.03°$). It is clear that a misalignment profile as the one in Figure 5a would result in unacceptable attitude estimates for the mission. Figure 5b finally reports the results of the applied method. It can be seen that the method correctly works with the EKF and the SMO. The main disadvantage of the use of the EKF is that it turns out to provide an attitude estimate that does not fulfil the requirement continuously along the orbit. Specifically, the points at which attitude estimation is most critical is when SRS must perform a rapid attitude change in

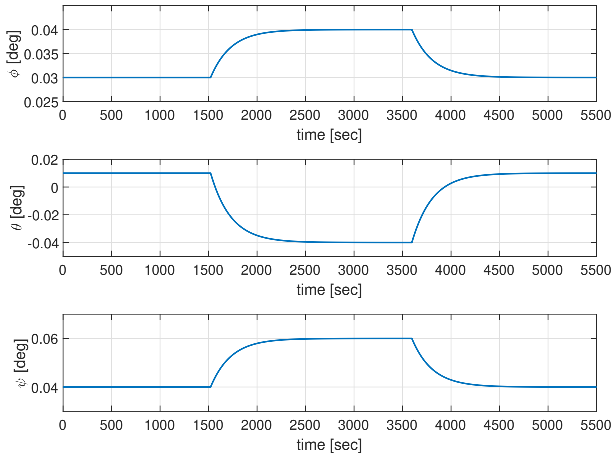
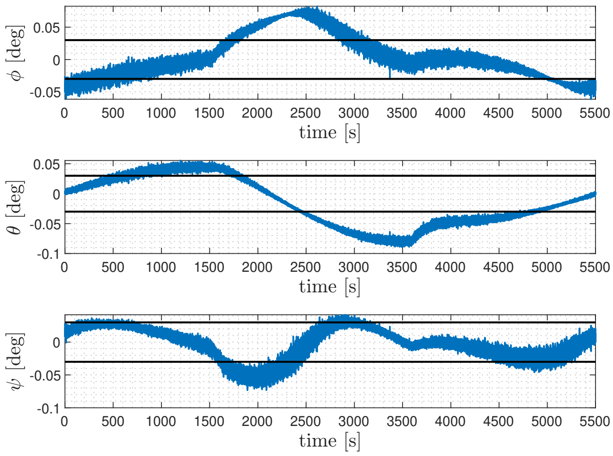
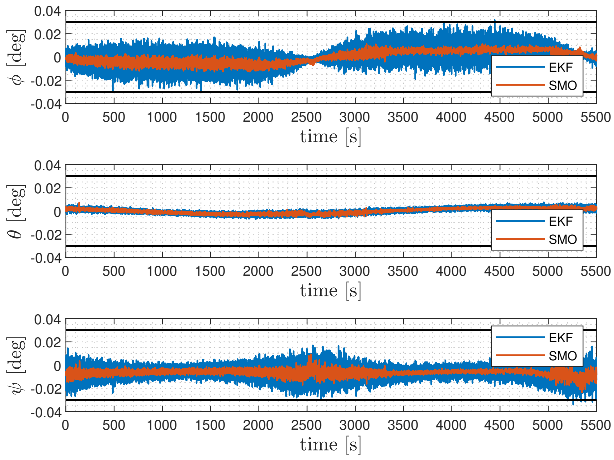


Figure 4: STR misalignment along the orbit



(a) No compensation



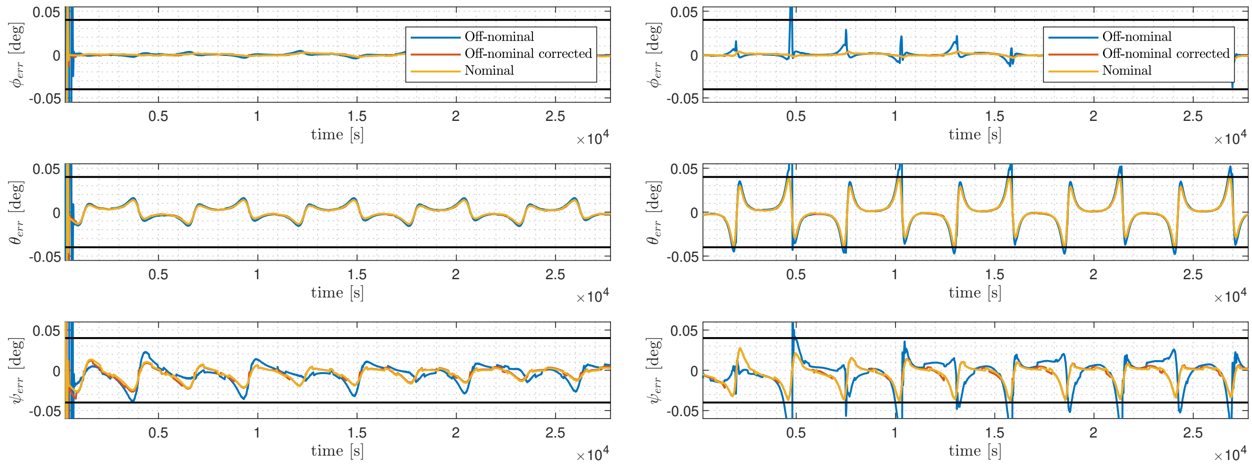
(b) Compensation method applied

Figure 5: STR Attitude pointing error

order to guarantee the orientation of the MPCG at Nadir and contemporaneously ensure sun following. It is worth remembering that the errors in the STR are also a function of the spacecraft's angular rate and therefore a degradation of performance at these moments is to be expected. The main advantage of SMO is that it allows more accurate results overall. Although the inherent misalignments of the STR are still visible (bias and low-frequency errors) and are independent of the chosen observer as it should be, by using an SMO with its non-linear injection term, it is possible to obtain an estimate that significantly reduces the attitude error high-frequency oscillations. Furthermore, analyses highlight how the attitude error is more dependent on the variation of the spacecraft attitude along the orbit than on the magnitude of the misalignment itself. It can be said that the performance of the identification and compensation method is independent of the magnitude of misalignments but depends on the stability and precision of the observer.

5.2 Reaction Wheel off-nominal behaviours

The loss of efficiency of the actuator can be constant, due to problems with electronics, lubrication deficiencies and problems involving slow changes over time, or time-dependent, usually related to the rotational speed of the RW. The latter is due to high-speed wheel dynamics, including problems related to lubrication or side effects which might arise over a certain speed. A second consideration



(a) $\beta = 29.7°$ (b) $\beta = 16.8°$

Figure 6: Attitude error: Single Off-Nominal RW

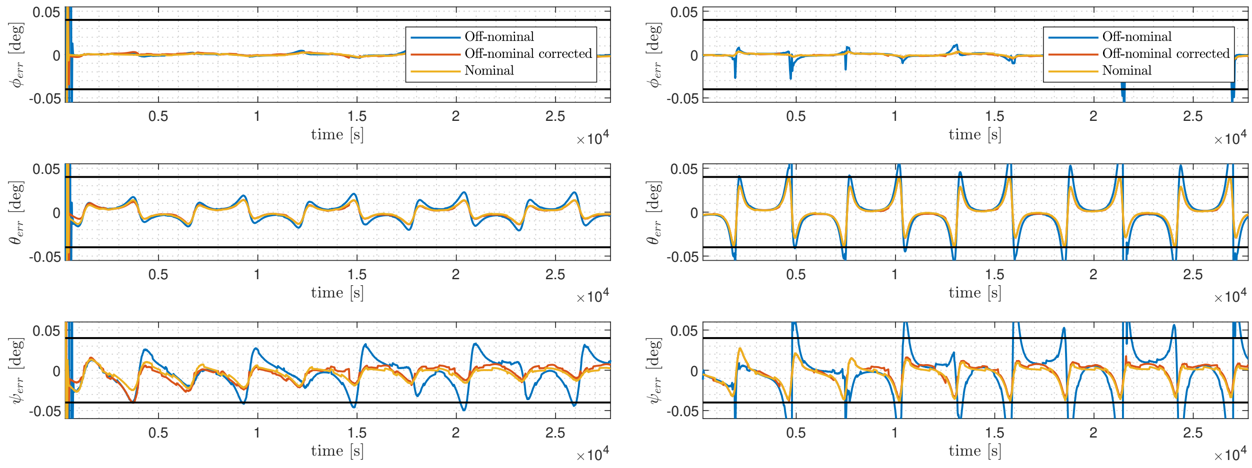
must be made about the simulated operating condition. During B2N attitude keeping, to guarantee a perfect Sun following, SRS have to perform oscillations around the Nadir direction. This attitude oscillation is more rapid and thus demanding for actuators when β[1] angle decrease. To overcome this problem a sub-optimal and less demanding Sun following mode is available on-board, but for an optimal solar array exposure it is advisable to keep the nominal mode as long as possible. Analyses are therefore carried out for different β angles, and results will be assessed on the basis not only of the attitude control errors but also on the operative conditions faced by RWs, in terms of actuated torque and saturation.

In this first set of simulations, a 50% efficiency is set on the second RW, and in addition, the efficiency of each RW is reduced by 15% when the rotational speed exceeds $3000rpm$. The simulations are performed on 5 orbits, which correspond to approximately 8 hours of operations, and the black line indicates the control error requirement ($0.04°$). The first simulation reproduces a condition where $\beta = 29.7°$, which is one of the most favourable conditions, while the second one reproduces a condition where $\beta = 16.8°$. Three simulations are shown in the graphs: one is performed on the system which is under a nominal functioning (*Nominal*), the second on the system whose RW has a degraded behaviour but without correction algorithm (*Off-nominal*), and the last one uses a system where the RW has again a degraded behaviour, but to which correction algorithms are applied (*Off-nominal corrected*). Figures 6a and 6b show attitude errors. It can be clearly seen that the applied method provides much more accurate results, in which the resulting errors are of the same order of magnitude as in the nominal simulation, i.e. the controller error. By reducing β (Figure 6b), the application of the identification and compensation method is crucial in order to fulfil the attitude error requirement. It can be seen that by having faster attitude changes to guarantee Sun following with higher torque required, any deficiency on a wheel results in large errors. The same considerations can be made for angular velocity errors, where errors increase sensibly each time SRS rotates.

In the second set of simulations is considered a case study in which 3 RWs have suffered a loss of efficiency, while the simulation environment and the external conditions are the same. Specifically, the 1st RW has an efficiency of 50%, the 2nd RW has an efficiency decreasing from 100% to 40% during the first 5h, constant afterwards, while the 4th RW has a constant efficiency of 70%. Moreover, the efficiency of each RW is again reduced by 15% when the rotational speed exceeds $3000rpm$.

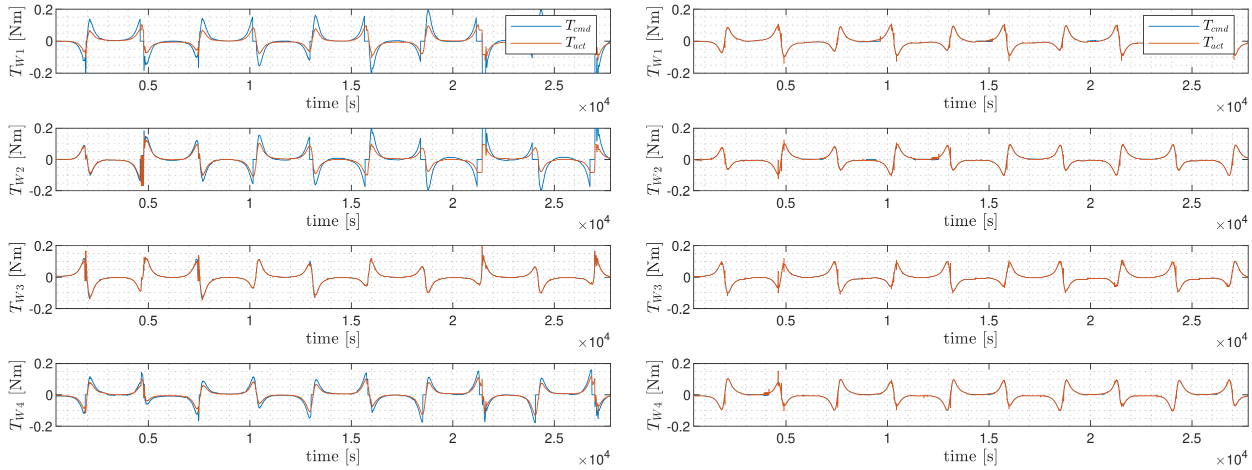
Figures 7a and 7b show again attitude errors. In contrast to the previous case, it can be seen here that with a larger number of off-nominal actuators, even in the condition with a high β angle, without the

[1] β is the angle between the satellite's orbital plane and the geocentric position of the Sun



(a) $\beta = 29.7°$ (b) $\beta = 16.8°$

Figure 7: Attitude error: Multiple Off-Nominal RW



(a) RW Off-Nominal Torque (b) RW Off-Nominal Corrected Torque

Figure 8: Torques: Multiple Off-Nominal RW ($\beta = 16.8°$)

compensation it would not be possible to remain within the requirements on attitude error, as shown in Figure 7a. It is also noteworthy that without applying the method, errors tend to increase over time and they become increasingly detached from the ones of the corrected case. Moving on to the case where $\beta = 16.8°$ in Figure 7b, errors in the uncorrected case are much higher, and the tendency is that these errors increase in amplitude as time progresses. With reduced efficiencies on multiple actuators, it is clear how the uncorrected system reallocation struggles more and more to follow the desired states having multiple causes of discrepancy; on the other hand, the system with the applied correction method shows again very promising results, managing to achieve attitude estimation errors fully comparable with the ones of the nominal case. A remarkable difference is visible in the trend of the commanded and actuated torques in the off-nominal case with and without correction. This time, multiple RWs work off-nominally and thus figures provide torque trends of each RW. Figure 8a shows the behaviour of the off-nominal system without correction, and as it can be seen there is a reduction in commanded torque of factors e_i. As noted earlier, a higher commanded torque means higher errors ahead. The final effect, i.e. the actuated torque, is comparable to the case in which the correction is applied (Figure 8b), where however the error wrt the desired stated is kept bounded. Although a very similar actuated torque results by using or not the applied method, it might be thought that the method is not so useful in the end. To disprove this statement, it must be remembered that in addition to having smaller state errors, the method allows having a system without discrepancies in the actuation, a fact of fundamental importance in the life of a system in orbit. In fact, in a hostile space environment, it is important to identify any discrepancy between expected and executed behaviour. Classifying these off-nominal RW functionings allows for a greater chance of identifying any other off-nominal system behaviours, reducing then the risk of a superposition of effects that would inevitably lead to greater uncertainties.

6 CONCLUSIONS

In conclusion, it can be stated that the applied methods allow for increased GNC performances. The two methods dealt with different problems but gave satisfactory results by using simple models and making simple considerations. Undoubtedly, however, methods present some criticalities that will be listed below, and on which further study would be necessary. The misalignment compensation of STRs makes use of the sliding mode observer and aims to compensate for unknown potential misalignments of sensors in orbit. It is difficult to have *a priori* information on the magnitude and the variability of these misalignments, and consequently, it should be demonstrated that the observer is able to guarantee the required performance over a wide range of situations. With regard to the behaviour of the RWs, the study was limited to one specific case of malfunctioning, which even though it is a consequence of multiple failure causes, it does not include all failure cases. The first action needed would be to expand the study to include more degraded cases and integrate them all into a FTC.

ACKNOWLEDGMENT

This work is the result of a Master's Thesis work, conceived and developed on behalf of AVIO S.p.a., under the supervision of Marco Giannini, reference of the Orbital GNC, and Christophe Roux, senior technical advisor. The academic supervisor is prof. Elisa Capello.

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