COMET INTERCEPTOR: AOCS/GNC DESIGN CHALLENGES FOR FLYING THROUGH THE DUST ENVIRONMENT OF A COMET

P. Bodin [(1)], F. Giuliano [(1)], R. Courson [(1)], L. Stenqvist Hanbury [(1)],
E. Zaccagnino [(2)], G. Della Pietra [(2)], D. Morea [(2)],
A. Hyslop [(3)], C. Corral van Damme [(3)], M. Sanchez-Gestido [(3)], N. Rando [(3)]

[(1)]OHB Sweden, Kista, Sweden, per.bodin@ohb-sweden.se

[(2)]OHB Italia, Rome/Milan, Italy, elio.zaccagnino@ohb-italia.it

[(3)]ESTEC/ESA, Noordwijk, The Netherlands, andrew.hyslop@esa.int

ABSTRACT

The Comet Interceptor ESA mission was selected by the Science Programme Committee in 2019 as a Fast track (F) mission. The mission aims to intercept a Dynamically New Comet or an Interstellar Object in a flyby scenario where the main spacecraft releases two smaller probes, where one of the probes is provided by JAXA. The spacecraft will be launched into the Sun-Earth Lagrange Point 2 (SEL2) and will wait there up to typically 3 years until an interesting target object is identified. The spacecraft will then enter a transfer trajectory taking between 0.5 and 4 years after which the spacecraft enters its final approach and encounter phase. The encounter phase requires fully autonomous operations and will include flying through the inner part of the comet coma at a distance of approximately 1000 km. The main challenge of the mission is to ensure the mission performance and survivability in this cometary dust environment taking into account the expected relative velocity range from 10 to 70 km/s.

This paper summarizes the main design challenges from an AOCS/GNC perspective from flying through the cometary dust environment and provides an outline of the resulting subsystem architecture. The paper also provides an overview of the verification strategy and provides some preliminary simulation results.

1 INTRODUCTION

Comet Interceptor is an ESA mission with payload contributions from ESA member states and with an international participation by JAXA. It was selected by the Science Programme Committee (SPC) in 2019 as a Fast track (F) mission [1]. Following a parallel competitive phase A/B, in late 2022 a consortium led by OHB Italia has been selected for the implementation phase (C/D/E1), with OHB Sweden leading the development of the AOCS/GNC and propulsion subsystems.

The mission aims to intercept a Dynamically New Comet or an Interstellar Object in a flyby scenario using the main spacecraft complemented by two smaller probes where one of these probes is provided by JAXA, in this way gathering multi-point observations of the comet and its coma.

The spacecraft will be launched towards the Sun-Earth L2 (SEL2) Lagrange point where it will wait up to typically 3 years until an interesting target object is identified [2]. The spacecraft will then initiate a transfer phase which will last between 0.5 and 4 years. The final approach starts approximately 60 days before encounter and will include ground-based navigation using on-board cameras. The encounter for the main spacecraft occurs at a nominal distance of 1000 km from the comet nucleus with a relative velocity between 10 and 70 km/s. To be able to allow the imaging scientific instruments to track the comet nucleus throughout the encounter, it is necessary to also implement on-board autonomous relative navigation functions.

The flyby of the comet through the central coma region involves a dust environment, which highly affects the spacecraft design to ensure that the spacecraft survives and fulfils its performance requirements. The dust environment and its appearance to the S/C are expected to dynamically change because of the surface topology of the comet nucleus, its surface activity and rotation, and because of changing lighting conditions. Considerations include potential blinding or reduced performance of star trackers from straylight, sufficient control authority and bandwidth to react to dust impacts, and autonomous navigation challenges given the uncertainty in target shape and illumination.

This paper describes the different challenges to design the AOCS/GNC that allows flying through the cometary dust environment. The key driving requirements are identified, and the resulting subsystem architecture is outlined. The paper also describes the approach for performance verification and provides some preliminary simulation results.

The paper is organized as follows. Section 2 gives a brief overview of the encounter phase of the Comet Interceptor mission including the main operational stages to be performed. Section 3 discusses the key driving requirements for the AOCS/GNC subsystem and Section 4 summarizes the main aspects of the resulting subsystem architecture. Section 5 provides an overview of the main performance verification activities while Section 6 gives some very preliminary results.

2 OVERVIEW OF THE ENCOUNTER PHASE

The Comet Interceptor mission includes three spacecraft, where S/C A is the main spacecraft and two probes, probe B1 and probe B2. The probes are released from S/C A in the final approach just before the start of the encounter phase. The final approach includes targeting maneuvers of S/C A for the release of the probes and a final correction maneuver after release of the probes. The approximate timeline of the main events relative to the closest approach (CA) is as follows:

- CA-44 h: Targeting maneuver for the release of probe B1
- CA-30 h: Targeting maneuver for the release of probe B2
- CA-16 h: Final targeting maneuver of S/C A
- CA-13 h: Switch to autonomous guidance of S/C A
- CA+6 h: End of S/C A autonomous tracking

The timeline includes several additional activities such as ranging, ground computations, parameter upload and initialization and commissioning of on-board navigation.

The geometric conditions of the flyby are illustrated with Figure 1. The figure shows the relative flyby velocity vector (in green) defined as the difference between the heliocentric velocities of S/C A and the target object at the time of CA. The B-plane, shown in yellow, is perpendicular to the relative flyby velocity vector and cuts through the center of the target object. The impact vector, shown in red, is the vector from the center of the target object to the point where S/C A passes through the B-plane. The flyby plane, shown in blue, passes through the center of the target object and contains the impact vector. The solar aspect angle, defined as the angle between the Sun and the relative flyby velocity vector can vary between 45° and 135° for different encounter scenarios.

The orientation of S/C A during the encounter is to keep the rotational axes of the solar arrays perpendicular to the flyby plane and to keep the surface of the dust shield perpendicular to the relative flyby velocity. This results in an attitude orientation of S/C A that protects the spacecraft against the dust environment in the central coma region and that keeps the rotational axes of the Rotating Mirror Assembly (RMA) and of the IR spectral imaging instruments (MIRMIS) scanning devices perpendicular to the flyby plane, such that the target object can be observed by providing the correct guidance angle to these devices.

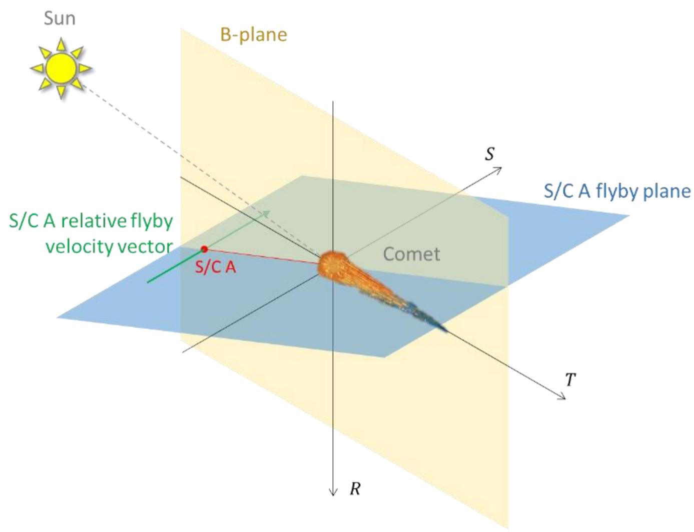

Figure 1: Flyby geometric conditions.

3 KEY DRIVING REQUIREMENTS TO THE AOCS/GNC DESIGN

This section presents what is considered to be key driving conditions and requirements for the AOCS/GNC design.

These include constraints and performances imposed by the scientific payloads, the operations near the encounter with the comets, the fact that the flyby is one single occasion with no opportunity for a second flyby, and the fact that the flyby occurs in a dust environment that is not well known.

3.1 Scientific Instruments

The primary goal of the Comet Interceptor mission is to characterize a long period comet (LPC), potentially being a dynamically new comet (DNC), or an interstellar object (IO). The science of the mission is split between *comet nucleus science*, focusing on surface composition, shape, morphology, and structure of the target object, and *comet environment science*, investigating the composition of the coma, and how this environment connects to the nucleus activity and interacts with the solar wind.

As in most missions, the scientific payloads put conditions on the design of the spacecraft in general and also on the fundamental design of the AOCS/GNC.

The scientific instruments on S/C A are:

- CoCa (Comet Camera): A high resolution colour camera for the imaging of the surface of the comet nucleus and its inner coma, illuminated through the Rotating Mirror Assembly (RMA).
- MANiaC (Mass Analyzer for Neutrals in a Coma): A mass spectrometer for in situ measurements of the coma.
- MIRMIS (Multispectral InfraRed Molecular and Ices Sensor): Multispectral infrared mapping of the ice and mineral composition of the comet nucleus and coma, and measurements of the nucleus surface temperature
- DFP-A (Dust, Fields, and Particles suite): Several in situ detectors for electrons, ions, energetic neutral atoms, dust, and magnetic fields.

CoCa and MIRMIS are remote sensing instruments that drive the pointing requirements of S/C A. The combination of closest approach distance and flyby velocity results in maximum angular rate of more than 4°/s of the LoS from S/C A to the target and as a result of a trade-off in the phase A of the mission, it was decided that slewing the whole spacecraft at this rate would require a substantially different spacecraft design than what was possible within the available budget and heritage design. In particular, slewing inside the coma region would require protecting several sides of the spacecraft against impacts from dust particles. The trade-off was made against including scanning devices allowing the remote sensing instruments to observe the comet throughout the encounter phase. As a result, CoCa is combined with a single-axis Rotating Mirror Assembly (RMA) while MIRMIS is equipped with an internal scanning mirror combining four sensors in near, medium, and thermal infrared bands.

The pointing of S/C A reduces in this way to keeping the rotating axes of the S/C A perpendicular to the flyby plane while at the same time providing guidance information to the scanning devices describing the LoS between S/C A and the target object. Dust shield protection of the spacecraft is in this way only needed on the panel perpendicular to the relative velocity direction.

The in-situ payloads MANiaC and DFP-A put restrictions on the use of thrusters during the encounter and the need to avoid contamination from the thrusters on the instruments has resulted in an un-balanced thruster configuration that is not able to provide force-free torques.

Additional instruments are accommodated onboard the two small probes, including a combination of remote sensing and in-situ measuring units.

3.2 Encounter operations and on-board navigation

The final operational phases before the encounter involve the release of the two probes and the associated targeting and correction manoeuvres of S/C A. The final contact with the S/C via the fixed High Gain Antenna is expected to occur at approximately 13 hours before the closest approach. The corresponding distance from the comet is between 500,000 km and 3,500,000 km while the distance at closest approach is targeted at 1000 km. At this distance from the closest approach, it is not possible to determine guidance information to the instrument scanning devices with sufficient precision based on ground-computations only. As a result, it is necessary to implement an on-board camera-based navigation capability, that allows to autonomously estimate and predict the LoS to the comet. One trade-off made in phase A had the purpose to decide on whether to include the navigation camera (Navcam) on the same RMA assembly as used by CoCa or to have body-fixed orientation of the navigation cameras. The outcome was in favour of the body-fixed camera solution since the inclusion on the RMA of another camera proved to be difficult in terms of physical accommodation, mechanical interfaces, and system verification. The resulting body-fixed design resulted in a combination of Wide Angle Cameras (WAC) and Narrow Angle Cameras (NAC) used to provide LoS measurements that are fed into an on-board navigation filter that allows to estimate and predict the LoS to the comet nucleus, the flyby plane, and the time of closest approach.

3.3 One-shot characteristic of the mission

Many missions contain critical operational phases and events with strong requirements on reliability. For deep-space missions this may concern e.g. critical orbit insertion manoeuvres or landing phases. The Comet Interceptor mission also contains critical orbit manoeuvres, but the criticality of the encounter phase is especially severe since there is no possibility at all to recover the main scientific purpose of the mission in case the spacecraft is not fully operational throughout this phase.

Since there will be no possibility for interaction with ground during the encounter phase, it is necessary to be able to accurately predict the system behaviour in the encounter phase environment and to ensure that operation is not interrupted as a result of reconfigurations and recover actions. These two aspects affect the spacecraft AOCS/GNC design and development since the functions critical to the encounter phase need to be validated in representative conditions, and since the system must be able to operate with hot redundant equipment in this phase.

Validation of Behaviour in Dust Environment

Because of the high relative flyby velocity, S/C A can travel up to 3,500,000 km from the time of last ground contact until the closest approach is reached. The observation conditions near the closest approach are in this way fundamentally different from those at the last interaction with ground, and there are only limited possibilities for in-flight calibration or tuning of the associated navigation cameras and the way they are used in the on-board navigation functions. Validation has to rely on realistic simulations and modelling including optical stimulation of the navigation sensors with realistic comet images and with complex modelling of the central coma dust environment.

As a result, a predevelopment activity was initiated already in phase A/B1 to develop a hardware-in-the-loop environment for optical validation of the navigation camera in cooperation with the Navcam potential supplier; see [3]. The environment is based on a dynamic optical Ground Support Equipment in combination with image generation software that is able to generate images of representative comet nuclei and their dust environment based on a reference dust environment model [4], and with further additions of jets, and outer coma artefacts.

Fail Operational Functionality

The spacecraft needs to be able to continue its operation in the presence of single failures in any on-board unit. For the AOCS/GNC, all sensors and actuators need to function in hot redundancy to allow for quick reconfiguration, change to redundant equipment. This requires an adaptation of several existing AOCS/GNC functional software modules in order to be able to support such uninterrupted operation.

3.4 Dust environment

The dust environment in the central coma region forms a challenging environment both in terms of mechanical impact on the spacecraft and in terms of optical disturbances for attitude and navigation sensors.

Mechanical Impact

With relative flyby velocities between 10 and 70 km/s, the mechanical dust impact on the spacecraft constitutes a significant hazard for the spacecraft. Both the spacecraft body and its solar panel edges are equipped with dust shields to protect the spacecraft against dust particles. However, the dust shield layout allows only a de-pointing of 3° before the spacecraft becomes damaged such that the spacecraft may become inoperable. Therefore, de-pointing resulting from the impact of dust particles drives not only the scientific output of the mission but also the survivability of the spacecraft.

In this way, the dust environment requires the AOCS/GNC to react promptly to dust impact disturbances with control functionality that is sufficiently agile and powerful.

Direct consequences for the AOCS/GNC are that the sampling frequency needs to be selected higher than what is normal for a mission with this class of pointing requirements, and that simultaneous use of thrusters and reaction wheel actuators will be necessary.

Optical Dust Effects

The spacecraft will fly between the Sun and the comet nucleus, and the dust particles will reflect sunlight that will have an effect on navigation and attitude sensors.

In the central coma region, is expected that navigation sensors will operate on very short integration times such that effects from the dust are expected to be limited. Optical effects resulting from dust are expected to be limited for this reason.

For attitude sensors, the optical effects from the dust will have an impact on the operability in the central coma region. The following aspects have been assessed:

- Straylight background
- Occultation of stars
- False stars
- Pixel saturation

The most significant effects are expected to be from the straylight background. The initial assessment of the straylight demonstrates that the background level will not be uniform.

Preliminary assessment for the AOCS/GNC show that degradation in the attitude determination can be expected during the close encounter to the comet and in the worst case, it is expected that there will be an outage of attitude measurements in the most central parts of the coma. The AOCS/GNC will in this way need to have the capability to propagate the attitude based on rate measurement with sufficient accuracy.

4 RESULTING SUBSYSTEM ARCHITECTURE

The sensor and actuator suite as well as the functional design of the Comet-I AOCS/GNC are to a large extent based on flight heritage from different OHB LEO and GEO missions. The functionality required during the encounter phase requires however both the development of new functionality and significant modification of existing designs.

The attitude control functionality will require significant modifications to be able to fulfil the performance requirements as well as ensuring the safety of the spacecraft under the mechanical impact from the dust environment. The modifications include control laws that allow simultaneous use of reaction wheels and thrusters for attitude control, a robust high bandwidth controller, and the use of hot redundant equipment to ensure seamless operation in the presence of failures in AOCS/GNC sensors and actuators.

4.1 Navcam configuration and navigation filter approach

The on-board relative navigation function is necessary for two main purposes. The function is needed to accurately determine the flyby plane (see Figure 1) so that the spacecraft can be oriented with the RMA and MIRMIS scanning mirror axes perpendicular to the flyby plane. The function is also needed to estimate the observation angle to the comet and the time of closest approach to be able to provide the necessary guidance information to the scanning devices.

Navcam Configuration

Trade-off studies and inventory of existing Navcam systems have resulted in a configuration with a combination of Narrow Angle Cameras (NAC) and Wide Angle Cameras (WAC). The NAC is needed to be able to detect and track the comet at the beginning of the autonomous phase. The WAC is needed in the very final parts of the encounter phase before the CA. The Line-of-Sight (LoS) of the cameras are offset with respect to the relative flyby direction to allow for the best possible navigation performance throughout the encounter phase. The camera configuration is illustrated with Figure 2.

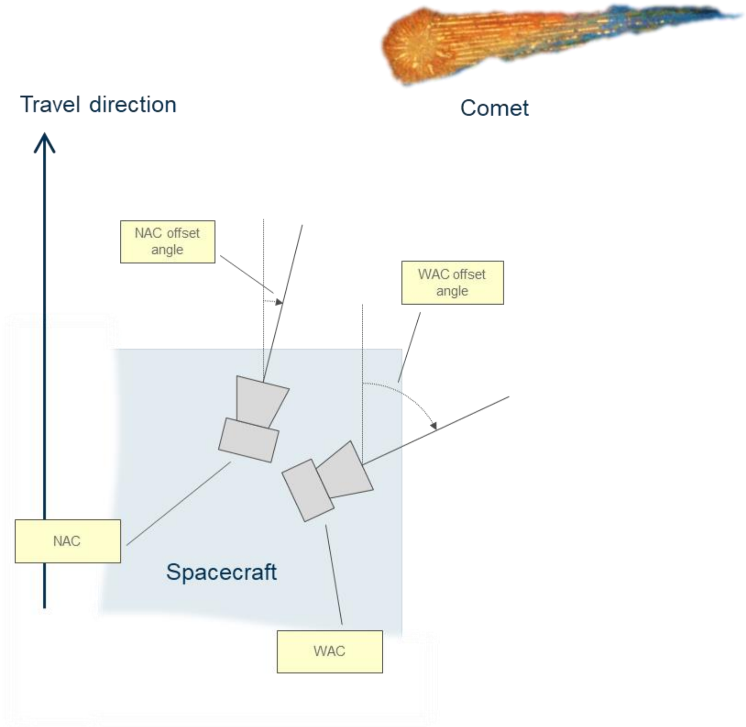

Figure 2: Navcam configuration.

One of the key requirements in the Comet Interceptor mission is to demonstrate sufficient technology readiness of technical solutions already in the A/B1 phase. This required a Navcam solution that could demonstrate heritage of relevant deep space operation as well as the possibility to demonstrate operation in simulated conditions through predevelopment activities in the Comet Interceptor A/B1 phase. The outcome of trade-off studies taking into account the above preconditions, together with mass and cost constraints resulted in a Navcam configuration offered by the Technical University of Denmark (DTU). The configuration consists of nominal and redundant Data Processing Units (DPU) and four cross-strappable cameras consisting of a nominal and redundant WAC and two different NACs. One of the NACs is devoted to the ground-based navigation starting at least one month before the CA. The other NAC is used in the first part of the autonomous phase. The two NACs can be used as mutual redundant back-up with slightly reduced performance. A fully redundant NAC configuration was not considered possible to implement due to cost and accommodation constraints.

The selected Navcam includes as a baseline a full heritage software where only tuning is expected to allow for detection of the direction to the target object. The Navcam system includes also a Dynamic Optical Ground Support Equipment (DOGSE) [5] that allows to display a comet image to the NAC or WAC cameras. The DOGSE consists of a display and a lens system in combination with a computer that provides the image display to the cameras. A realistic real-time comet display framework based on Blender [6] is under development by OHB Sweden allowing for closed loop simulations in an Avionics Test Bench environment, or alternatively, on the PFM spacecraft.

Note also that the Navcam heritage solution allows the WAC and NAC to also operate as star trackers allowing for convenient co-alignment calibration with the Star Tracker cameras.

Navigation Filter

The measurements provided by the Navcam system consist of CCD positions which are transformed into directional angles in the AOCS/GNC software. Here, also the comet object is selected among several candidate objects based on the expected direction and intensity.

The directional measurements are then fed into the Relative Orbit Navigation function which consists of an Extended Kalman Filter based on a rectilinear trajectory model which allows to estimate the flyby plane orientation and the distance to the target object at CA. Based on the filter estimates, the functions is able to provide continuous updates of the necessary guidance information to the RMA and MIRMIS payloads.

The relative navigation function includes FDIR functionality to validate the filter innovations as well as the possibility to fall back to a pre-defined guidance profile in case the filter fails to perform as expected.

4.2 Star tracker operation in straylight conditions

One of the challenges in the Comet Interceptor mission is to predict the appearance of the dust environment for the Navcam and Star Tracker optical sensors. For the Navcam, it is expected that the target object will be bright in the central coma region and that the effects from over-all straylight from the coma will not be significant with the integration times for an object this bright. The Star Tracker, on the other hand, operates at longer integration times and the effects from the straylight from the dust are expected to be significant.

The Star Tracker selected for Comet Interceptor is provided by DTU and is based on similar equipment with a DPU in combination with two Camera Head Units (CHU). As discussed above, operation of the Star Tracker in the dust environment was evaluated with respect to occultation, false stars, pixel saturation, and straylight background. The straylight was found to have the largest impact on the performance of the attitude determination capability. Moreover, the straylight is expected not to be uniform (see Figure 3 for a synthetic image generated from ESA analysis). The operation in the dust environment will be evaluated by DTU using the DOGSE environment in combination with straylight emulation on top of their normal star sky generation software.

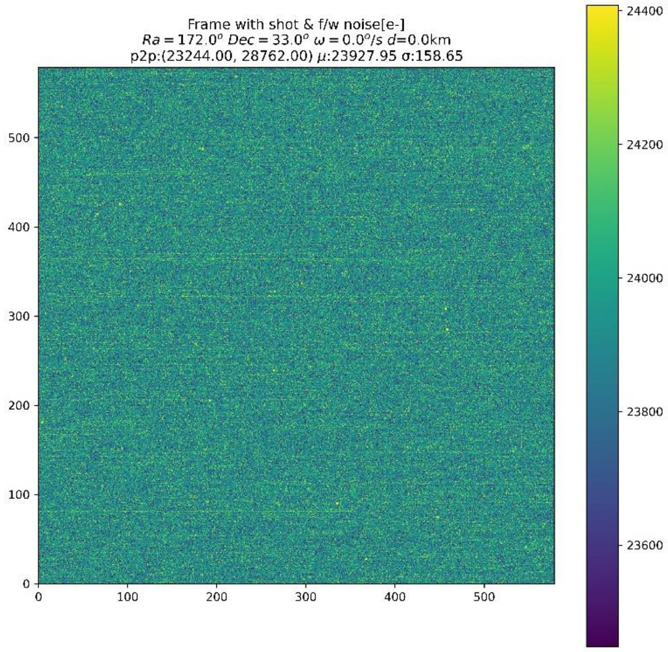

Figure 3: Synthetic star tracker image (units e-) at closest approach.

It is expected that the Star Tracker will experience increased noise, intermittent outages, or complete measurement outage in the central coma region. As a result, the AOCS/GNC design has been modified to include a fibre optic gyro with better performances than what would be needed if continuous star tracker measurements could be assumed. The gyro offers good performance in terms of Angular Random Walk (ARW) but more importantly, the fibre optic technology offers a very low Rate Random Walk (RRW) which in the case of Comet Interceptor allows to keep the pointing performance throughout the encounter phase even if the Star Tracker will not provide attitude measurements in the central part of the coma.

The relatively low ARW provides also better agility in the attitude estimation and improves in this way the system responsiveness to mechanical impact of dust particles.

4.3 Fail operational design

In addition to maintaining pointing performance throughout the encounter phase, it is also necessary to maintain spacecraft safety by ensuring that the angle between the relative flyby velocity vector and the normal of the dust shield never exceeds 3°. The short duration of the encounter phase will also not allow for any significant recovery or reconfiguration of on-board equipment so it will be necessary to use as much as possible of the AOCS/GNC equipment in hot redundancy or to at least keep the equipment on, operational, and ready to use.

The need to promptly respond to dust impact has resulted in an attitude control design that simultaneously uses the reaction control system thrusters (RCS) and reaction wheels (RW).

A literature survey was performed to find different control approaches that simultaneously uses reaction wheels and thrusters. In the case of reaction wheel failures, thrusters have been used together with reaction wheels in a hybrid control setting. [7] summarizes the results from the first NASA Cross-Center Hybrid Control Workshop. The workshop was motivated by a number of recent RW failures in NASA spacecraft. For similar reasons, [8] summarizes development of hybrid control for the Cassini spacecraft in preparation of loss of reaction wheel controllability.

Attitude control with simultaneous momentum management where attitude control is based on reaction wheels while the momentum is managed with thrusters is a common way to simultaneously use these actuators. Simultaneous control using reaction wheels and thrusters were proposed for large space structure control in [9].

Finally, thrusters can be used in combination with reaction wheels in a fine and coarse control setting where thrusters are used to improve the capability to rapidly repoint the spacecraft while the reaction wheels provide the fine pointing capability, see e.g. [10]–[12]. These methods are similar to the fine/coarse control approach normally used in several OHB heritage designs. The following variant of the approach was investigated.

Multivariable feedback control coupled with hybrid RCS and RW actuation was found to be a good fit for Comet Interceptor, as it is a method to infer robust performance and robust stability while pushing the envelope of maximum torque actuation of the spacecraft.

The control structure is inspired by a standard coarse-fine controller structure where the coarse controller is based on a PD-controller design and where the derivative part is tuned to give maximum actuation if a particular angular momentum is transferred to the spacecraft, here based on the impact from particles with mass greater than a certain value hitting the edge of the spacecraft dust shield or the dust shield of the solar panels. The fine control is obtained from a robust controller design, tuned to achieve fast reaction and disturbance attenuation while constrained by the parametric uncertainty of the plant, mainly mass properties and solar panel flexible dynamics.

The RCS or RW actuator system is selected based on the controller torque demand such that if the demand exceeds the predicted capability of the RW, the RCS is selected. The AOCS/GNC is operated in hot redundancy in the following way.

The Star Tracker is configured with one CHU used by the nominal DPU and one CHU used by the redundant DPU. The measurements from the two respective CHUs are included into the on-board attitude estimation filter separately by the normal design of the filter.

Both gyro units are switched on simultaneously. As long as no unit level error is detected for the nominal unit, this unit is used in the AOCS/GNC. In case an error is detected, and the unit is invalidated, measurements from the redundant unit replaces the nominal one.

Measurements from the nominal Navcam branch is used in the navigation function while the redundant branch is active and ready to replace the measurements that go into the navigation function. In terms of actuation, all RW units are used in hot redundancy and can seamlessly reduce to three units in case a unit level error is detected. The AOCS/GNC will use the RCS branch available.

4.4 Summary of AOCS/GNC encounter phase architecture

The spacecraft layout is illustrated with Figure 4. The figure shows S/C A in its encounter model configuration with the two probes mated. The relative velocity direction is "upward" and the dust shields can be seen on top of the solar panels and on top of the spacecraft itself. The solar array rotational axes are kept normal to the estimated flyby plane and the "target-facing panel" will be oriented towards the target object at the CA. The panel contains the Navcam, Star Tracker cameras, and the MIRMIS and RMA payloads.

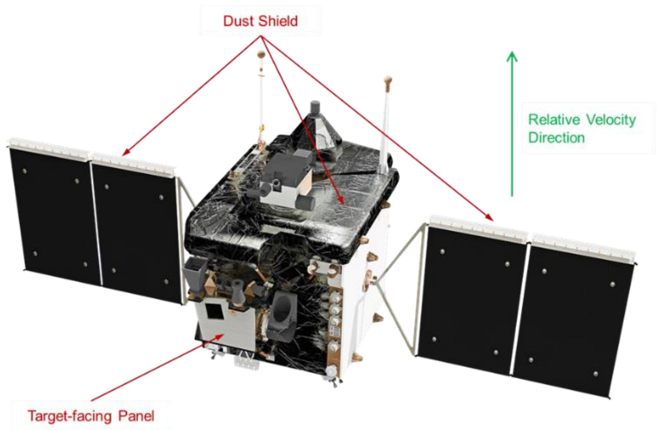

Figure 4: Comet Interceptor S/C A encounter phase configuration with mated probes.

The AOCS/GNC will be configured in a dedicated Encounter Mode during the encounter phase. The functional architecture of the mode is illustrated with Figure 5. The figure shows the main functional modules of the AOCS/GNC and how these are fed with sensor data and how they provide the actuator commands. The complete AOCS/GNC application software is integrated as a part of the overall Satellite Control Software (CSW). The CSW feeds the AOCS/GNC software with sensor data and distributes the unit level actuator commands computed by the AOCS/GNC to the actuator units. The Star Tracker, Gyro, Navcam, and Reaction Wheel processing modules convert the raw sensor values into engineering values. The *Attitude Estimation* function uses the gyro and attitude measurements to provide an estimate of the spacecraft's attitude. The attitude is used together with the Navcam measurements in the *Relative Orbit Navigation* function to provide the state estimate relative to the target object. This state estimate is used in the *Comet Tracking Guidance* function to provide a guidance attitude that keeps the spacecraft oriented correctly in the currently estimated flyby plane. The navigation state is also used to provide the guidance information to the RMA and MIRMIS payloads. The attitude estimate and the guidance attitude are used in the *Feedback Attitude Control* function to compute the respective torque demand from the Reaction Wheels and the Reaction Control System. The corresponding actuator management functions then compute the unit level demand from the actuator assemblies.

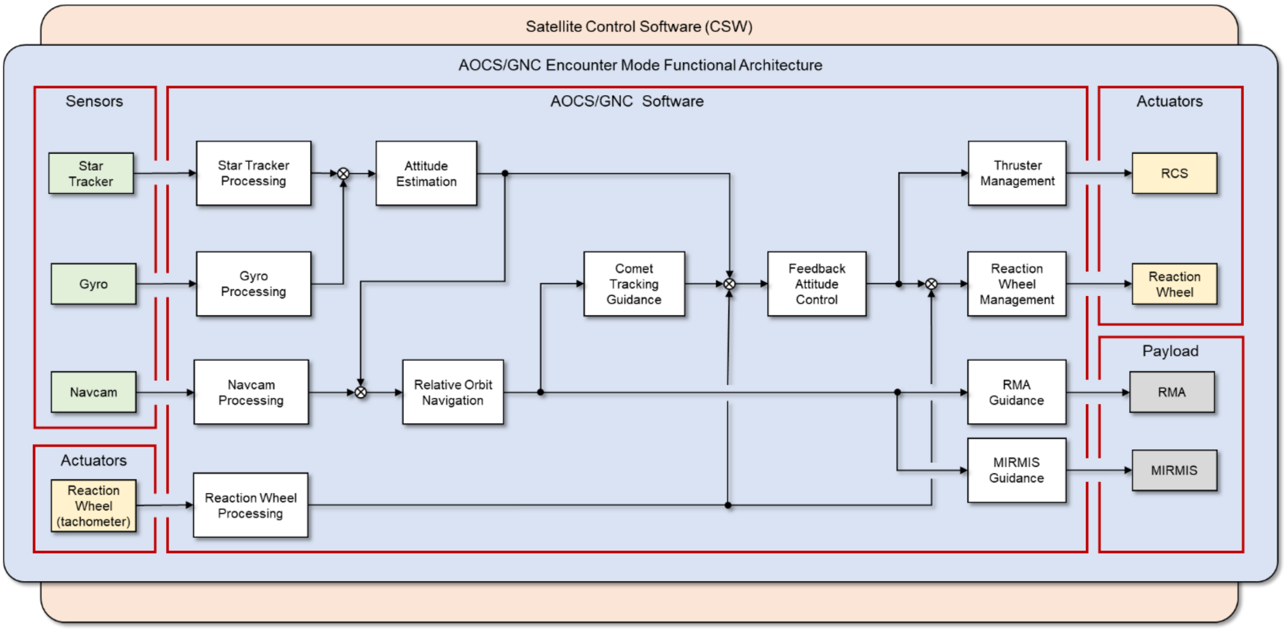

Figure 5: AOCS/GNC Encounter Mode functional architecture.

5 PERFORMANCE VERIFICATION APPROACH

The verification approach is divided into three main parts:

- Hardware-in-the-loop optical stimulation of Navcam sensors.
- Performance verification simulations
- Avionics Test Bench (ATB) and PFM satellite testing

A hardware-in-the-loop optical simulation environment is developed together with DTU based on their Dynamic Optical Ground Support Equipment where a comet image generation framework is developed by OHB Sweden that allows the display of representative comet images corresponding to the view of the respective Navcam cameras. The image generation is developed to be rendered in real-time with a reasonably low delay in order to support closed-loop Avionics Test Bench and PFM spacecraft testing. The hardware-in-the-loop tests of the Navcam also serve as a test environment to gather statistical information in different scenarios to support the parameterization of a behavioral model of the Navcam measurements. The behavioral model is statistically representative of the hardware-in-the-loop simulations and will be used in the performance verification simulations. The hardware-in-the-loop Navcam tests are described in [3].

In the performance verification simulations, the behavioral model is used to model the Navcam measurements in the flyby simulation environment. This environment is based on advanced Simulink simulation models taking into account all relevant model features of the system in the encounter phase. This includes detailed behavioral models of the sensors and actuators, flexible dynamics, and a particle impact model based on the statistics from the EDCM [4]. The performance verification simulations are used to verify the performance and survivability requirements from a statistical perspective. The basis for the encounter cases is, in addition to the particle impact statistics, also the statistics of the flyby which takes into account the dispersions in distance at closest approach, the relative flyby velocity, and the orientation of the flyby plane.

The ATB and PFM closed loop simulations will make use of an AOCS/GNC SCOE, developed by OHB Sweden, which includes a real-time dynamics and environment simulator, sensor and actuator models and emulation of their hardware interface connections. The SCOE will be connected to either the ATB, consisting of Engineering Models (EM) of avionics with a reduced set of AOCS/GNC sensors and actuators, or to the PFM spacecraft. The SCOE is connected to the DOGSE which stimulates Navcam and/or Star Tracker cameras that are connected to the ATB. The DOGSE is developed so that the comet image generation continuously takes into account the attitude of the spacecraft. The setup allows closed loop simulations including various degrees of hardware-in-the-loop and in particular optical closed loop stimulation of the Navcam cameras.

6 PRELIMINARY SIMULATION RESULTS

This section provides some preliminary results from the hardware-in-the-loop Navcam simulations and the flyby simulations.

Figure 6 shows examples of comet image views sent to the DOGSE display. The left picture shows the view sent to the NAC 10,000 km before the CA wile the right picture corresponds to the image sent to the WAC 1000 km before the CA. The left image shows that some stars will be visible at this distance with the NAC while for the WAC image shown in the right picture demonstrates that no stars are expected to be visible.

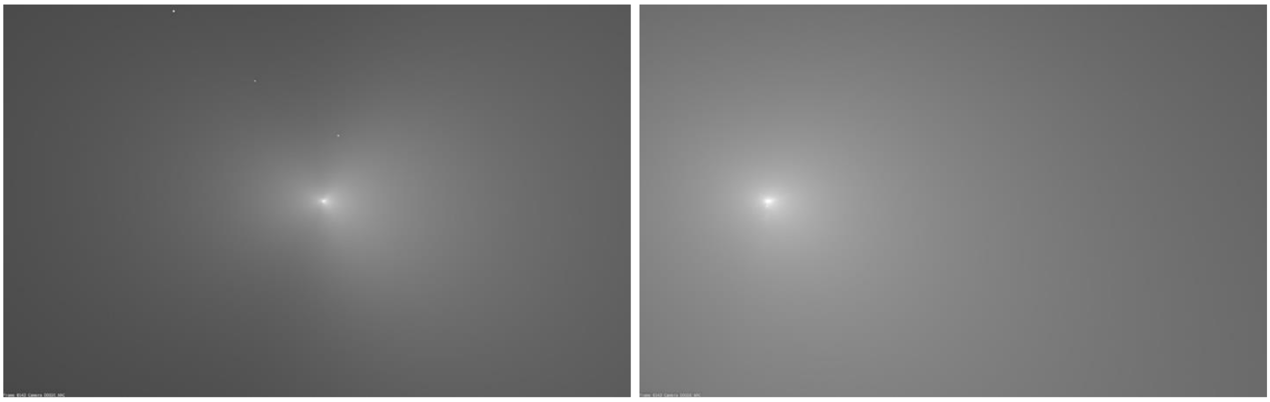

Figure 6: DOGSE view sent to the Navcam cameras.
Left: NAC 10,000 km before the CA. Right: WAC 1000 km before the CA.

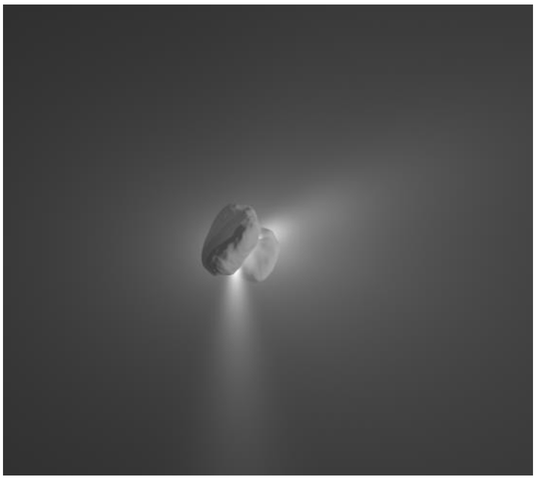

Figure 7: Typical 0.69°×0.92° CoCa view, with jets enabled.

Figure 7 is included to demonstrate the versatility of the display framework developed. The figures show what could be expected in a CoCa view. Here, the image generation framework includes also the simulation of jets. The nucleus displayed is based on comet 67P.

Figure 8 shows some very preliminary results from the Monte Carlo flyby simulations. The top plot of the figure shows the pointing error during the encounter phase starting from approximately 30 minutes before the closest approach. The bottom plot shows the probability distribution for the maximum error. The plots show that there are a few cases where the impact from dust particles result in significant pointing errors but that the error is less than 3° in all of the cases in the shown scenario. The simulations include dispersions in the distance at CA as well as the relative flyby velocity.

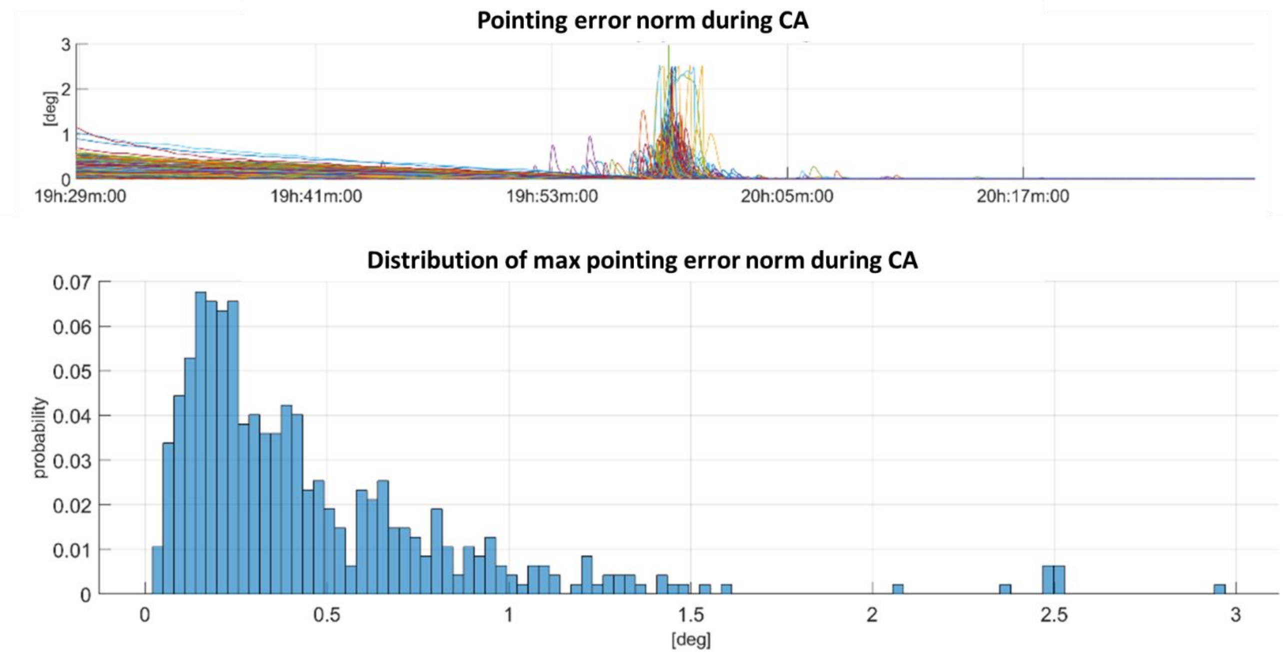

Figure 8: Results from flyby simulations.

7 CONCLUSIONS

This paper demonstrates some of the AOCS/GNC design challenges associated with flying through the dust environment close to a comet. The paper summarizes the main driving aspects and discusses how these have influenced the subsystem design. The paper also outlines the approach for verification and validation and provides some very early simulation results. The paper concludes that the system relies on an on-board navigation function that uses a Navigation camera system to determine autonomously on-board the observation angle towards the comet nucleus and its time evolution. Since the operation of this on-board system will be challenging inside the dust environment, the paper also concludes that the verification approach depends on detailed and realistic simulation models of the dust environment and the comet nucleus.

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