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Maximizing Autonomy on a Small Satellite Platform

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ABSTRACT

OHB Sweden’s future generation InnoSat microsatellite platforms will see a large upgrade in the platform’s functionality maximizing onboard autonomy. In this paper, three development lines will be presented each contributing to maximizing efficiency and autonomy on a small satellite platform.

The InnoSat platform is a flexible platform concept with a recurring catalog of units, recurrent onboard software and mission control software, and heritage AIT processes. Two InnoSat missions are currently flying: Swedish National Space Agency's MATS and the commercial bring-into-use satellite GMS-T. Two more InnoSat derived missions will be launched in 2024: ESA's Arctic Weather Satellite and Satlantis' Garai-A. In 2025, Garai-B and Space Norway's ADIS are expected to be launched. Several other InnoSats, such as ESA's EIS IOD and ESA's Aurora-D, are in phases C and B respectively, in addition to multiple phase 0/A studies.

The three autonomy development lines are focusing on satellite control (ASK), constellation control (OPTACOM), and onboard agility (OPCMG).

The Swedish National Space Agency funded study Autonomous Station Keeping (ASK) adapts the existing ground-based InnoSat mission analysis and flight dynamics tools for autonomous use onboard. A Model Predictive Control scheme is in development and will be implemented in the InnoSat AOCS software and tested in the InnoSat Satellite Simulator. The expected Eumetsat EPS-Sterna constellation of Arctic Weather Satellites is a candidate for first flight of the ASK algorithm.

The ESA funded OPTimized Autonomous Constellation Orbit Management (OPTACOM) study is a cooperation between OHB Sweden, OHB System, DLR, and Luleå Technical University (LTU). OHB Sweden provides the use case, a large constellation based on the InnoSat platform, with three test scenarios: constellation initialization, station-keeping, and constellation reconfiguration. Collision avoidance is treated as a constraint in all three scenarios. Both embedded real-time optimization and machine learning will be explored and compared with a benchmark feedback control solution. Two simulators will be developed, one for algorithm development and training, and one high-fidelity simulator for final verification with hardware characterization.

OPCMG is an ESA funded study on autonomous and optimized agile attitude control with CMGs for small satellite platform. The study is conducted by OHB Sweden and is performed in cooperation with DLR and deals with the onboard implementation of autonomous CMG guidance and control. Within the study, the use of embedded onboard optimization is compared with adaptive control techniques to solve the combined problem of optimal slew motion, and CMG guidance and control to ensure long-term efficient commandability under varying observation conditions.

INTRODUCTION

On-board autonomy has been considered as an important area for satellite missions over the last few decades. The development within newspace with large constellations, advanced payloads, and also cost reductions and more streamlined operations results in further increase in the demand of automated operations and improved onboard spacecraft capabilities.

Recent advances in on-board computational capacity, embedded optimization, and in artificial intelligence provide enabling technologies which allow to meet the demand to increase satellite autonomous capabilities[1,2,3,4].

This paper provides some examples of on-going activities within the area of spacecraft autonomy currently considered for the future generation of OHB Sweden's InnoSat satellite platform.

The paper first provides some background for the different areas considered and then summarizes the different development directions taken. The paper then gives some examples and intermediate results from on-going development activities and finally provides some concluding remarks.

BACKGROUND

Three different areas within small satellite autonomy are treated in this paper: Onboard Autonomous Orbit Control, Constellation Management, and Attitude Agility. The sections below provide some background and justification for these areas of automation.

Onboard Autonomous Orbit Control

OHB Sweden has developed the Arctic Weather Satellite (AWS) under ESA contract[5,6]. The AWS mission will be launched in July 2024 and is a forerunner of a constellation of satellites, called EPS-Sterna, that ESA would build for Eumetsat if the first prototype Arctic Weather Satellite works well.

The EPS-Sterna mission is envisaged as a constellation of six microsatellites in three orbital planes in order to provide almost continuous temperature and humidity data from every location on Earth. The constellation allows for improved nowcasting and Numerical Weather Prediction (NWP) especially over the Arctic and Antarctic regions.

The aim of the AWS project is to qualify a prototype satellite to be used for the constellation. An additional design target is to minimize the operational cost for the constellation driving onboard autonomy and operability. Constellation missions like the Arctic Weather Satellite (AWS) mission have strict requirements to maintain its orbital position in order to maintain the associated ground track for a long time (up till 5 years mission duration). What might be manageable to solve manually for a single satellite becomes unnecessary cumbersome, complex, and costly to for a larger constellation.

Figure 1: Arctic Weather Satellite.

The requirement originally discussed for AWS was to maintain ±5 km ground track relative to the reference, together with the requirement of four days without ground commanding. With the low thrust EP system on AWS, this requires autonomous onboard orbit control.

Such onboard orbit control was not possible to implement within the budget of the AWS development project the requirement has been relaxed for the precursor mission. It is however expected that an improved performance is highly desirable for the EPS-Sterna constellation.

Implementation of onboard orbit control for the EPS-Sterna constellation would not only increase the overall mission performance but also reduce the constraints on the ground segment.

Constellation Management

In general, the management of satellite constellations requires complex orbit control management often with short response times and sometimes the need for fast reorganization of the orbital configuration to handle manage satellites.

One way to manage these requirements is to enhance spacecraft onboard autonomy to be able to manage the spacecraft cluster in terms of orbit phasing to obtain the desired coverage and to avoid collisions and return to mission continuity after failure. Similar techniques are successfully implemented for UAV guidance and self-landing rockets[7,8].

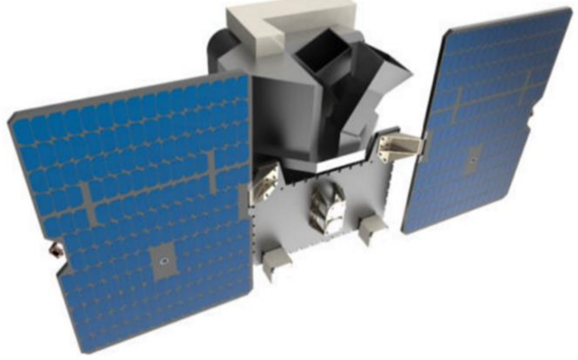

Figure 2: Render of EIS satellite configuration.

In view of the aforementioned EPS-Sterna constellation as well as other mission opportunities, OHB Sweden sees the inclusion of such enhanced onboard autonomy in its future generation InnoSat.

Attitude Agility

There is a strong trend in miniaturization for satellites carrying imaging payloads and many future InnoSat prospect missions are within Earth-imaging. Certain applications such as maritime surveillance require a certain degree of agility and in general, an improved agility provide drastic enhancements in imaging coverage capabilities. This includes not only the increase in covered area but also the ability to e.g. observe an area that requires several parallel tracks during the same satellite pass, or the ability to quickly reach a certain area with short notice.

One key element to provide such agility to a satellite is the torque capability of the actuators but also the ability to manage the associated quick change of angular momentum. In addition, a small satellite will have limited power capacity so the commandability must be achieved in a way that is efficient in terms of power as well as mass. Several suppliers of reaction wheels also provide Control Moment Gyroscopes (CMG) and some suppliers are currently developing CMGs suitable for small satellite platforms.

One of the key challenges for implementation of CMGs on a small satellite is to be able to handle singularities associated with “gimbal-lock” and to plan attitude profiles, actuator guidance and momentum management to avoid such situations or to manage them in a controlled way. Also here, it is evident that enhanced onboard autonomy will improve the usability of such a platform.

General Aspects of Enhanced Autonomy

As noted above, future small satellite missions are often developed for advanced applications involving constellations, precise orbit maintenance, or agile Earth observation. Often, there are commercial aspects and constraints which do not allow the customer to staff operations teams, or to procure operations, which include specialists on flight dynamics, optimization, or other expert areas associated with the mission. For these reasons, it is expected that in general, future advanced applications will require a large degree of onboard autonomy in combination with advanced ground-system tools and procedures also those with enhanced capabilities in terms of automation and flexibility.

DEVELOPMENT DIRECTIONS

This section summarizes the development directions in view of the background areas provided n the previous section. The directions are associated with different on-going studies.

Onboard Orbit Control

To be able to advance development for future constellations, with aim for the EPS-Sterna constellation, OHB Sweden conducts a development activity called Autonomous station Keeping (ASK). The activity is funded by the Swedish National Space Agency (SNSA) with co-funding by OHB Sweden and aims at adapting existing ground-based mission analysis and flight dynamics tools for autonomous use onboard.

The main part of the activity consists of developing a Model Predictive Controller (MPC) that is suitable for the low-thrust Electric Propulsion system carried by AWS, and to adapt the controller such that it is possible to execute in the onboard real-time embedded software environment.

The activity aims also at validation of the developed solution in the InnoSat Satellite Simulator within an adaptation of the AWS AOCS software.

The ASK study is expected to provide a software module for onboard orbit control that is possible to accommodate in the standard AWS onboard software and hardware computer platform.

Constellation Management

OHB Sweden conducts the ESA funded OPTimized Autonomous Constellation Orbit Management (OPTACOM) study, which is conducted together with OHB System, DLR, and Luleå Technical University (LTU).

The main objective of the study is to evaluate methods based on Embedded Real-Time Optimization and Machine Learning separately on three different test scenarios and to evaluate the performance of these two methodologies against a benchmark feedback control solution.

Apart from managing the study, OHB Sweden's role is to provide the use case and to develop a high-fidelity simulator.

The use case consists of a large constellation that is based on the InnoSat platform. Three different test scenarios are defined within this use case:

- Constellation initialization
- Station-keeping
- Constellation reconfiguration

The simulator developed by OHB Sweden is a high-fidelity simulator that will be used for final verification with hardware characterization.

Control Moment Gyroscopes

OHB Sweden conducts ESA funded study on Autonomous and Optimized Agile Attitude Control with CMGs for Small Satellite Platforms (OPCMG). The study is conducted together with DLR.

The study includes the definition of a study mission case that is representative of small satellites and also the definition of observation scenarios for this mission.

The study mission case is based on the European IOD/IOV Satellite (EIS) mission[9]. EIS will host a single experiment from the Belgian company AMOS called ELOIS[10], which is a compact hyperspectral instrument, developed to be suitable for remote sensing small satellites.

The main activity of the study is to investigate the performance of embedded optimization and compare this to heritage solutions that are based on adaptive control techniques. The problem can either naturally be separated into an attitude guidance control problem with separate guidance and control of the CMG constellation in this way exploiting its null-space kernel, or can it be treated as an over-all guidance and control problem including attitude as well as the overdetermined CMG actuator configuration. Different combinations of the above approaches are evaluated in order to arrive at a preferred synthetization of the problem. The study also includes the execution of optimization algorithms on a flight-like hardware computer board.

The study is currently being finalized and its outcome will be separately reported.

While DLR implements the parts associated with embedded optimization, the parts developed by OHB Sweden consist of an adaptive control scheme which provides means for CMG null-space control that makes sure that a certain degree of torque availability is guaranteed, and that singularities of the CMG constellation are avoided. The result from the adaptive controller is slightly less performant than the scheme based on embedded optimization, but it offers simple operative rules suitable for a streamlined operational approach.

STUDY STATUS AND PRELIMINARY RESULTS

The sections below demonstrate some preliminary results from the different studies mentioned above.

Autonomous Station Keeping

So far in the Autonomous Station Keeping study, a 6 DOF Model Predictive Controller (MPC) has been implemented in Matlab.

The controller solves the station keeping problem for a mission which implements electric low-thrust propulsion.

The Matlab implementation of the MPC works in combination with GMAT and uses the QSQP (Operator Splitting Quadratic Program) solver numerical optimization package to solve the convex quadratic program that is associated with the station keeping problem.

The next step in the study is to constrain the problem to use only one thruster together with slew rate limitations for out-of-plane maneuvers. A constraint with regards to maximum duration of thrust in one orbit will also be applied.

Constellation Management

The management of a satellite constellation involves three primary optimization scenarios: constellation initialization, station-keeping, and constellation reconfiguration. Each scenario focuses on optimizing time, fuel efficiency, and operational availability while ensuring collision avoidance through the incorporation of Collision Avoidance Maneuvers (CAM).

The following three scenarios cover the key phases of satellite constellation management.

Initialization

This scenario involves the deployment and initial positioning of satellites after their release from the launcher.

Station-Keeping

This scenario focuses on maintaining the satellite constellation in its designated configuration over time.

Reconfiguration

This scenario deals with reconfiguring the constellation in response to satellite failure or temporary unavailability.

CMG

The CMG study included the treatment of a six-CMG configuration which provides a three-dimensional momentum null space that provides flexibility for momentum allocation to guarantee good torque availability for the planned slew maneuvers in this way avoiding gimbal lock singularities. The six-CMG configuration is illustrated with Figure 3.

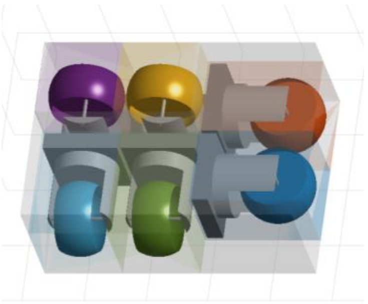

Figure 3: Example of six-CMG configuration.

The adaptive controller developed for the mission relies on an attitude controller that takes into account the available torque for the planning of the slew maneuver. The torque availability is guaranteed through a separate CMG kernel guidance function which guarantees torque availability. The kernel guidance is parameterized in a way that allows to characterize the torque availability by quantifying the invertibility of the associated allocation matrices.

Figure 4 shows a mapping of the determinant of the torque allocation matrix as a function of the CMG momentum kernel space parameterized through three variables η_1, η_2, η_3. The figures demonstrates that the matrix is invertible in all directions of this space. Figure 5 shows an example where certain directions in the kernel parameter space results in very low values of the torque allocation determinant thus, indicating singularities which in this way will provide very poor torque availability.

The studied parameterization provides a means to develop a guidance scheme which allows to select good working points for the CMG configuration in preparation of attitude maneuvers ahead.

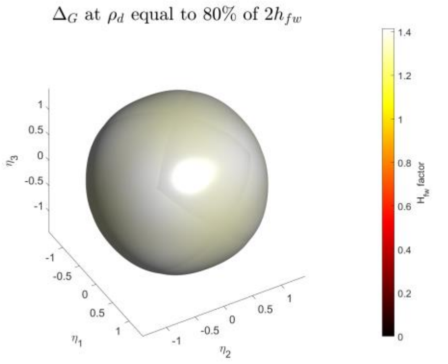

Figure 4: Torque availability without singularities.

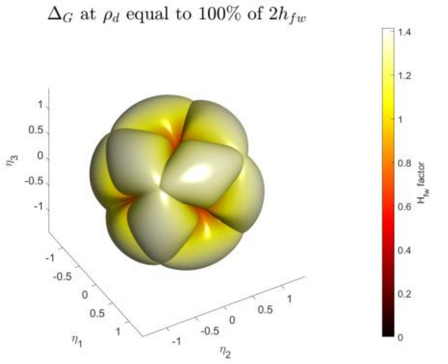

Figure 5: Torque availability with singular points.

Figure 6 shows an example of slew profiles for the study mission. The figure shows 10°, 30°, and 10° slews about the tree respective S/C axes. These slews constitute basic building blocks that allow for performing e.g. three parallel ground observation tracks during the same satellite pass. The duration is only a few seconds for each of these large angle slews.

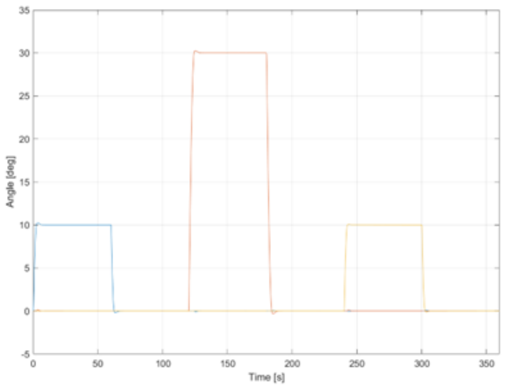

Figure 6: Example of slew profiles.

CONCLUSIONS

This paper has provided an overview of some the future trends foreseen for within autonomy of future small satellites and constellations. The paper summarizes the impact on the future of OHB Sweden missions and the activities conducted for the associated developments. Study status and preliminary results were also provided.

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