AIRBUS

DEFENCE AND SPACE

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TABLE OF CONTENTS

1 Executive Summary 1

1.1 Overview and Motivation 1

1.2 Mission Use Cases and Requirements Identification 1

1.3 Definition and Tuning of Adaptive Techniques 2

1.4 Validation and Verification Campaign 3

1.5 Hardware Implementation 3

1 Executive Summary

1.1 Overview and Motivation

The objective of the "Adaptable Attitude Control and Estimation with Guaranteed Robust Performance" (ACE) study was to industrialise parameter-varying and adaptable control and estimation methods that can deal with time-varying changes of spacecraft properties that are not known in advance, but can be measured or estimated in real time.

The study was conducted by a trilateral consortium led by Airbus Defence and Space GmbH Friedrichshafen with Airbus Defence and Space SAS Toulouse and Technical University of Dresden (TUD) as subcontractors.

As the academic partner, TUD identified the most promising state-of-the-art adaptable techniques and prepared or further developed them for application by Airbus. In addition, TUD performed a hardware-in-the-loop test of the selected linear parameter-varying (LPV) controller to assess its on-board capability.

As the industrial partners, Airbus selected three mission use cases with parametric variations representative of the entire portfolio of satellite missions (LEO, GEO, and science missions). The current (time-invariant) controller/estimator solutions served as baselines against which the adaptable techniques were evaluated. In addition, a processor-in-the-loop test was performed to assess the on-board capability of the selected LPV solution (complementing the hardware-in-the-loop test at TUD). Furthermore, the current industrial AOCS design and analysis process was extended by the potential use of LPV or adaptable techniques.

1.2 Mission Use Cases and Requirements Identification

A diverse set of parameter variation problems are present across the entire portfolio of satellite missions. Classically, parameter variations (whether known or unknown) are addressed using robust control design techniques, thus treating them as unknown by definition. This leads to increased conservatism and suboptimal performance for parameter variations that are measurable in real time such as:

- Solar array rotation: The variation of the spacecraft's mass properties can be estimated using the current solar array rotation angle measurement.
- Mode transitions are classically performed as hard switches, which cause transients and thus a potentially increased settling time into precision pointing phases.
- Sensor degradations due to e.g. increased angular rate of star trackers.
- Microvibrations that depend on reaction wheel speeds, which is a measured quantity.

Airbus has selected three representative missions to serve as case studies for these types of parameter variation:

- MetOp-SG (LEO mission)

  - Focus on mass property variation due to solar array rotation and fuel mass reduction after long burns
- Athena (science mission)
  - Mode transition from thruster-based slew manoeuvres to reaction wheel-based pointing phases
  - Star tracker accuracy degradation during large-angle slew manoeuvres
- E-NEO laser communications terminal (GEO mission)
  - Microvibration frequency variations due to reaction wheel speed

TUD has reviewed the academic state of the art with respect to sufficiently mature frameworks to tackle these types of parameter variations. The LPV framework has emerged as a promising synthesis and analysis technique for most of the problems described above, since most of them can be modelled in line with the LPV framework. For the LCT study case, which is not a typical LPV problem, a promising alternative approach was found that is also robust and adaptable.

1.3 Definition and Tuning of Adaptive Techniques

For both MetOp-SG and the Athena mode transition study cases, the nonlinear attitude dynamics were linearized in line with the existing industrial process, which yielded a set of parameter-varying linear models. The varying parameters were modelled with a clear distinction between unknown parameters (modelled as uncertainties) and measurable parameters (modelled as varying parameters in the LPV sense). Then, LPV controllers were synthesized using a mixed-sensitivity weighting scheme provided by TUD. In all cases, the controllers fulfilled all performance requirements and they were able to adapt to the parameter variation by adapting the closed-loop bandwidth accordingly (to account for either shifting flexible mode frequencies or varying torque capacities).

For the Athena attitude estimation study case, the gyro-stellar estimator (which fuses angular rate measurements from gyroscopes with attitude measurement from star trackers) was scheduled with the angular rate as varying parameter, leading to a corresponding variation of the estimator gain. This gain-scheduled estimator was then applied to a representative large-angle slew manoeuvre and its performance was benchmarked against a constant-gain observer and against a Kalman filter where the gain is recomputed at every time step.

For the laser communications terminal (LCT) study case, a novel robust and adaptable disturbance estimator was developed based on a fast Fourier transformation of the telescope’s pointing measurement and a pseudo-gradient method to determine both frequency and phase of the microvibration disturbances. With the thus obtained knowledge of the disturbance, a control signal is computed to cancel the disturbance.

Motivated by the positive synthesis results, the current industrial process was extended by an LPV synthesis and analysis part. This process extension included a set of guidelines to identify when LPV methods are likely to offer performance improvements over LTI methods and which methods (e.g., grid-based or LFT-based) should be used.

For all considered study cases, the design and tuning of adaptable controllers and estimators yielded promising results. All syntheses were successful and showed performance improvements over the baseline when applied to the design plants.

1.4 Validation and Verification Campaign

The adaptable and LPV controllers and estimators were implemented in various time-domain simulation environments as listed in the table below:

Study Case	Simulator
MetOp-SG NOM	MetOp-SG FAME
MetOp-SG OCT	Athena development simulator
Athena Mode Transition	Athena development simulator
Athena Gain-Scheduled GSE	Athena development simulator
LCT	LCT simulator

All simulations were performed with the full available level of fidelity (e.g., using detailed unit models) to ensure a fair comparison of the adaptable and LPV algorithms against the existing baselines. This approach also tests the controllers' and estimators' robustness against unmodelled effects such as more realistic sensor noise, quantization effects, etc.

While some of the performance improvements seen in the simplified analyses using the design plant were reduced, the adaptable and LPV algorithms still showed an overall performance improvement.

1.5 Hardware Implementation

To investigate the on-board capability of the advanced control/estimator algorithms, the MetOp-SG NOM study case was selected due to its maturity. At Airbus, the relevant algorithm block was extracted and autocoded for a target LEON3 on-board computer. Using an internal software verification facility, a processor-in-the-loop test was conducted with an emulated LEON3 processor and the computational effort was determined in terms of the required computation time.

In parallel, TUD set up a hardware-in-the-loop testbed configured in line with the LEON3 processor architecture. The same LPV controller was autocoded and run on the hardware while determining the required computation time.

In both tests, the computation time of the LPV controller was found to be in the order of milliseconds, which is roughly 10 times slower than the baseline LTI controller, but still fast enough to be implemented on board a typical satellite.