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Control Technologies at the European Space Operations Centre: Current Projects and Future Perspectives

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Abstract

Consolidated mission control approaches have been used at the European Space Operations Centre (ESOC) of ESA for many years and represent a solid basis and precondition for attaining mission success.

In recent years, however, increased mission complexity was not accompanied by an adequate increase of available resources. As a consequence increase of cost efficiency and increase of provided functionalities had to be pursued with all means. Control Technologies, in particular in the area of Artificial Intelligence and Automation are becoming a considered source to contribute for the fulfillment of the identified goals.

This paper presents an overview of the current ESOC exploitation of advanced control technologies in support of specific mission control processes, such as planning & scheduling, monitoring, control & diagnostic, resource management, off-line analysis. Case driven projects and implementation methodology are being presented and commented. Decision support systems to problems with unsharp input parameters, optimization of functions in extremely non-linear and discontinued search space and autonomous rescheduling are the themes that originated those problem cases discussed in the paper.

Benefits and lessons learned out of the current operational prototypes exploitation are then presented as well as an outline of a vision of the impact that such technology enabled exploitation might provide to the degree of automation of current flight operations approach and to the evolution of the spacecraft autonomy concept, in the long term.

1. Introduction

Consolidated mission control approaches have been used at the European Space Operations Centre (ESOC) of ESA [1] for many years and represent a solid basis and precondition for attaining mission success, as demonstrated by a long record of successfully operated and controlled missions.

In recent years, however, the mission complexity increased without a correspondent increased of available resources. As a consequence high priority has been set to identify viable means for achieving increase of cost efficiency of mission operations processes (e.g. planning, scheduling, monitoring, control, diagnostic, trend analysis, performance assessment) both during preparation and execution phases, without endangering the overall mission success and mission safety.

Another challenge to the current operations approach is being injected by space mission classes such as constellation/formation flying missions like Cluster, Meteosat, Galileo, SMART-3, Darwin and interplanetary missions, like Rosetta, Mars Express and Bepi Colombo. Multiple spacecraft control, off-line operations, increased autonomy, both on-board and on-ground, lights-out operations are among the main functional challenges.

2. Case-driven Technologies

In our operations control improvement projects the availability of enabling technology plays a fundamental role for the resolution of the specific problem case. However, careful attention has been given to the selection process of the suitable set of technologies: the set should be mature for industrial applications and fitting each individual problem class. With this attitude in mind fuzzy logic, genetic algorithms and artificial neural networks have been among the first techniques to match the first problems proposed by the operations community at ESOC. Synergy between the three initial technology choices has been also identified and evaluated, currently labeled with the term Soft Computing technique.

The availability of commercial and open-source tools supporting the selected technologies made it possible to rapid prototype and deploy the target applications.

3. Problem cases: a survey of recent developments

The identification of the operations control problem cases was made in competition across ESOC controlled missions, being either in the preparation phase or in the execution phase. Each flight control team has been invited to submit a proposal in response to an internal announcement of opportunity.

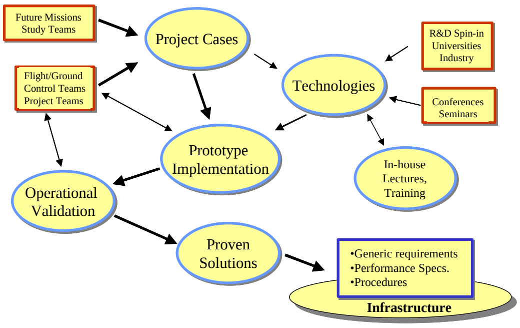


Fig. 1 – Control Technology Project Flowchart

The addressed areas of interests included tasks such as planning & scheduling, monitoring & diagnostic, resource management, off-line analysis. The criteria followed in the case selection process were respectively the urgency to solve cases not covered by available functionalities, the maturity of the case definition, the availability of data, the availability of a suitable enabling technology.

Current control technology projects have the operations community as main driver while the suitable technology is serving the case resolution. The prototype is not just delivered as demonstrator: the "operational prototype" is aimed to be integrated in a "non-invasive" and risk-free way with the operational environment. The requesting operations team will have this way the opportunity to use the tool and make an extensive validation and assessment of the improvements (see fig. 1).

3.1 Methodology for Development, Implementation & Operational Validation

Each project focusing on the resolution of the identified problem made use of fast prototyping approach derived from the Dynamic System Development Method (DSDM) [2]. We had three different iteration classes, named functional prototyping, design prototyping and operational prototyping.

Each iteration was focused respectively on requirement capturing, software design and interface design & tool deployment. The frequent deliveries where fixed on time and resources. The delivery content was identified based on a list of prioritized requirements negotiated at the beginning of each individual prototype cycling called time-box. A major objective of this approach was to get rid of the usual 40% and more functional requirements that usually become of no use in a traditionally developed SW application. Users involvement and testing were spread throughout the project development cycling.

3.2 ENVISAT Gyro Performance Monitoring Tool

Gyroscopes are instruments capable of sensing changes in their inertial orientation. A gyroscope has one or more sensitive axis and can measure a rotation around them. They are usually mechanical devices that employ a rapid spinning mass to detect the inertial variations. Satellites usually have gyroscopes in the Attitude and Orbit Control System as attitude (orientation) sensors that measure angular displacements. They are critical components with widely spread operational lifetime and often required to be constantly monitored during the duration of the mission. In face of serious failures, proper corrective actions are possible, but they depend on the time available for the spacecraft controllers to react.

Currently used gyroscope monitoring methods (low-level hardware checks and validation of operational parameters) are adequate for detecting failures that can happen in the short-term but fail to predict long-term failures. To detect these long-term degradation trends, spacecraft controllers perform detailed studies of the power spectral density properties of the gyroscope output. In a real situation, the decision made by the control team to declare a gyroscope faulty depends on a qualitative reasoning based on experience (see Fig. 2).

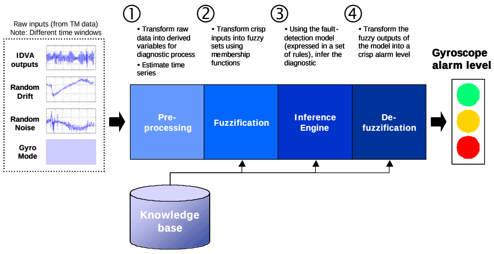


Fig. 2 – ENVISAT gyro monitoring functional steps

In this project [3] a model of gyroscope fault detection based on a fuzzy expert system solution that formalizes and captures the knowledge and experience gathered in previous missions has been designed and implemented. This expert system provides the ENVISAT flight control team, responsible for satellite operations, with a new type of gyroscope health diagnostic tool (see Fig. 3). This diagnostic tool generates alarms with different degrees of criticality and a severity level of the alarm itself, instead of a simple presence/absence of the alarm. It also supplies an explanation of the alarm and an in-depth analysis environment.

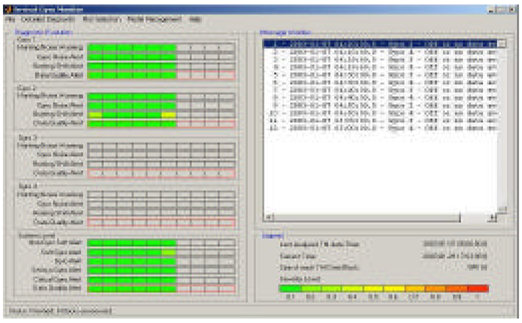


Fig. 3 – ENVISAT gyro monitoring tool

The tool is regularly used by the ENVISAT control team. It is expected to provide early warning and diagnostics of initial performance degradation of the operational gyros, well beyond the automatic on-ground or on-board detection of out-of-limit parameters. This additional piece of information will allow the operator to decide and implement preventive maintenance procedure of the gyro(s) without disruption of payload services.

3.3 Optimal XMM/INTEGRAL Reaction Wheels Bias Maneuver

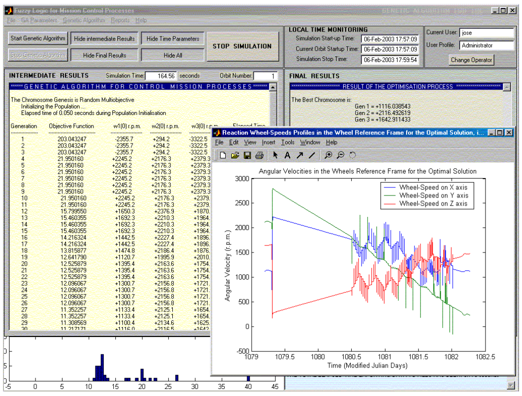
The XMM (X-ray Multi-Mirror) spacecraft consists of three X-ray telescopes and an optical/UV telescope. It was launched in December 1999 into a highly eccentric elliptical orbit (48 hours).

The INTEGRAL (International Gamma-Ray Astrophysical Laboratory) spacecraft is in charge of performing detailed spectroscopy and imaging of celestial gamma-ray sources. It has been launched in late 2003 into a highly eccentric elliptical orbit (72 hours).

Both spacecraft have a three-wheels momentum control system, which is used for all slews and for external torque compensation during routine phases where science observations are made. During pointing maneuvers a near zero wheel speed of any of the three active wheels has to be avoided. A zero crossing during a slew is allowed, providing the speed of crossing it not too slow. Also wheel saturation has to be avoided for slews as for pointing.

Before starting a new orbit the momentum desaturation maneuver should be performed in order to avoid wheels saturation or wheels stiction during the next orbit observations. This maneuver consists of changing the wheels speeds without changing the spacecraft attitude. So, it is necessary to generate a torque by activating thrusters in order to change wheels speed while maintaining the attitude.

The problem we went to solve here was to choose the most suitable speed for each wheel to save as much fuel as possible while all constraints for the next orbit are taken into account. The constraints that are to be taken into account are: wheel saturation, wheel stiction, solution feasibility and spacecraft stability, without modifying the target observation sequence.



LOCAL TIME MONITORING

Simulation Start-up Time: 06-Feb-2003 17:57:09
Current Orbit Startup Time: 06-Feb-2003 17:57:09
Simulation Stop Time: 06-Feb-2003 17:59:54

Current User: jose
User Profile: Administrator

INTERMEDIATE RESULTS Simulation Time: 164.56 seconds Orbit Number: 1

```
****** GENETIC ALGORITHM FOR CONTROL MISSION PROCESSES ******

The Chromosome Genesis is Random Multiobjective
      Initializing the Population ...
      Elapsed time of 0.050 seconds during Population Initialisation

Generation   Objective Function   w1(0) r.p.m.   w2(0) r.p.m.   w3(0) r.p.m.
----------   ------------------   ------------   ------------   ------------
    1            203.043247          -2355.7         +294.2        -3322.5
    2            203.043247          -2355.7         +294.2        -3322.5
    3            203.043247          -2355.7         +294.2        -3322.5
    4            21.950160           +2245.2         +2176.3       +2379.3
    5            21.950160           +2245.2         +2176.3       +2379.3
    6            21.950160           +2245.2         +2176.3       +2379.3
    7            21.950160           +2245.2         +2176.3       +2379.3
    8            21.950160           +2245.2         +2176.3       +2379.3
    9            21.950160           +2245.2         +2176.3       +2379.3
   10             21.950160           +2245.2         +2176.3       +2379.
   11             21.950160           +2245.2         +2176.3       +2379.
   12             15.799550           +1650.3         +2376.9       +1870.
   13             15.460355           +1692.3         +2210.3       +1964.
   14             15.460355           +1692.3         +2210.3       +1964.
   15             15.460355           +1692.3         +2210.3       +1964.
   16             14.216324           +1442.5         +2227.4       +1896.
   17             14.216324           +1442.5         +2227.4       +1896.
   18             13.815877           +1474.8         +2186.4       +1876.
   19             12.641790           +1120.7         +1995.9       +2010.
   20             12.525879           +1395.4         +2163.6       +1754.
   21             12.525879           +1395.4         +2163.6       +1754.
   22             12.525879           +1395.4         +2163.6       +1754.
   23             12.096067           +1300.7         +2156.8       +1721.
   24             12.096067           +1300.7         +2156.8       +1721.
   25             12.096067           +1300.7         +2156.8       +1721.
   26             12.096067           +1300.7         +2156.8       +1721.
   27             11.352257           +1133.4         +2125.1       +1654.
   28             11.352257           +1133.4         +2125.1       +1654.
   29             11.308569           +1100.4         +2134.6       +1625.
```

FINAL RESULTS

```
********************** RESULT OF THE OPTIMISATION PROCESS **********************

The Best Chromosome is:
                     Gen 1 = +1116.038543
                     Gen 2 = +2116.492619
                     Gen 3 = +1642.911433
```

Fig. 4 – XMM/INTEGRAL optimisation tool

It is a very difficult problem because solutions closed to good ones may be not feasible or not as good as they should be (small changes in the individuals produce big changes in their fitness). So we are dealing with a multimodal constrained function and special effort must be done not to get trapped in local minima.

Genetic Algorithm was considered a suitable technique to solve the optimization problem. The first prototyping [4] clearly demonstrated the benefits of the selected approach, however the expected improvement, in terms of fuel saving were not yet so remarkable. Further investigations convinced us to pursue the multi-objective genetic algorithm approach [5]: it consists of dealing with several objectives at the same time. There will not be a single solution but a set of solutions. These solutions are optimal in the sense that no other solutions would be better when all objectives are considered. They are known as pareto-optimal solutions. Extensive validation tests on real orbit cases demonstrated the possibility to reach up to an average of 35% fuel saving during the bias maneuvers, with respect to the current approach. Flight Dynamics is going to use the tool (see Fig. 4) for supporting INTEGRAL reaction wheels bias maneuver planning, as of Spring 2003.

Overall the benefits allow to achieve a significant mission extension, i.e. increase of mission product return.

3.4 XMM/INTEGRAL Radiation Monitoring and Operational Adjustments

The two European space observatory spacecraft XMM and INTEGRAL carry on board sensitive instruments with CCD sensors extremely sensible to radiation: they can be easily damaged if the CCD surface is reached by highly energetic particles such as those available in the earth radiation belts or those emitted by the sun during violent solar flares. The INTEGRAL flight control team identified the need to have a sort of decision support tool able to predict in time an upcoming increase of radiation around the spacecraft to early warn mission control and give the opportunity to safely plan and execute the required instrument safing procedure. A first implementation has been completed and is now under test. Curve fitting techniques have been used as first approach, although on-going investigation are also considering the use of Artificial Neural Network to capture the correlation between on-board sensors and externally available space environment measurements vis-à-vis non-nominal events.

3.5 PROBA Autonomous (Re-)Scheduler

The autonomous scheduling of on board tasks for space applications during normal and contingency operational phases was the subject of another investigation. The prototype implementation has been built taking as reference PROBA, an ESA technology demonstrator mission conceived for the purpose of demonstrating new on board technologies and benefits of on board autonomy.

The main payload is a Compact High Resolution Imaging Spectrometer the operations of which are based on the observation requests remotely transmitted from the scientists to the control centre.

The observation requests may clash with other on board operations such as achievement of particular attitudes for optimal solar power supply or downlink windows or may be in conflict with the on board resources such as power and available on board memory.

Thus an autonomous supervisor must achieve goals related to the payload as well as to the spacecraft housekeeping by managing limited power and memory resources, which play as constraints and activity priorities which, depend on the spacecraft state.

Moreover an eventual fault of an on board subsystem must be detected in order to autonomously activate a recovery mode.

The engineered solution is based on the use of fuzzy logic and predicate calculus techniques [6]. The allocation in time of the activities is managed as a constrained multi-criteria decision-making problem. A scalar function is built to transform the actual problem in a one-dimensional one. Both the starting and the final timelines for the update of the on board functions are not a priori fixed: a decision making block receives observation request number, coordinates as well as status parameters from the on board subsystems and through a fuzzy logic control block gives the duration and the starting time for the next scheduling process. If status parameters reveal a possible fault a recovery scheduling block is activated. The development is due to be completed in February 2003.

4. Expected benefits and lessons learnt

The results of the investigations are demonstrating that Artificial Intelligence techniques can provide benefits in improving the efficiency or augmenting the capability of specific operational tasks. It is required to identify metrics to quantify these improvements vis-à-vis the effort required for the investigation. One major area of improvement is represented by the decision making processes in existence of unsharp input parameters.

These prototyping implementation definitely are contributing in bridging the gap between what is being researched in the Academic world and the practical use of innovative and proved techniques and solutions applied to industrial processes, particularly in the area of mission control.

The development methodology so far used in the addressed cases enabled the flight engineer, owner of the operational knowledge and initiator of the case study, to actively contribute to the design and implementation of the prototype tools within the extremely limited available manpower. As a consequence the convergence to the most important issues to solve was definitely facilitated.

The average manpower implementation effort per case, including the development, the user support and the technical management is estimated to be around 8 man-months spent in 6 months.

The availability of historical data is very often a prerequisite for a successful analysis of the problem and the consequent identification of the appropriate enabling technology. This fact implies the need to recur to a “similar “ mission in case the proposing control team is working on a space mission not yet on orbit. This consideration also implicitly facilitated the beneficial cross-fertilization of operational problems and experiences across missions.

5. Medium & Long-term Visions

The positive experience and the encouraging results so far matured are affecting the potential increase of project cases, both in number and complexity.

On the medium term of 5 years we expect to have a consolidated classes of already resolved problem cases, with associated algorithms & tools ready to become an asset of our mission control infrastructure. Increased level of automation and performance at acceptable risk and integration of currently split functional systems are among the major objectives.

In long term we would expect that the matured and proven solutions might become also subject for on-board implementation, enhancing the current level of on-board autonomy. Intelligence proved on-ground can be then smoothly relocated on-board.

We would expect to have therefore increased on-board reliability with intelligent failure management system, improved near optimal decision making in particular when the input parameters are unsharp, on-board autonomous scheduler of activities and intelligent resource management systems.

6. Conclusion

ESOC is pursuing continuous improvement of its mission control processes, in term of cost efficiency and augmented functionality recurring, among other, to artificial intelligence and advanced control technologies.

This paper has discussed the case driven approach and the implementation methodology followed in past and ongoing projects. Four cases have been introduced. Lessons learned and medium/long term visions have been presented in relation to the implementation and operational validation of concrete case projects.

The positive results so far demonstrated provide comfort in further exploitation of artificial intelligence to serve mission control processes.

Reference

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