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FUZZY LOGIC APPLICATIONS FOR ADVANCED SPACE MISSION CONTROL FUNCTIONS

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Abstract

Fuzzy Logic (FL) has become a mature technology to be applied in domains such as process control, decision support system, optimisation.

In this framework investigations have been carried out at the European Space Operations Centre (ESOC) of the European Space agency (ESA) on the potential use of Fuzzy Logic to implement specific applications in support of mission control functions. The investigations are aimed to support new requirements derived from upcoming complex and challenging missions and to facilitate operations cost reduction.

The paper will provide a summary of the implemented cases and the lessons learnt from them, including the areas of applicability of FL based tools for supporting mission control processes and the preconditions required for a successful modelling and implementation.

The paper will conclude with potential plans for future advanced mission control applications, making use of synergies between FL and other available technologies.

1 Introduction

ESOC is a satellite operations control centre supporting mainly scientific, technological and earth observation missions.

Flying a mission can be performed in different ways characterised by specific effectiveness, efficiency and degree of mission safety. At ESOC, with its 43 successfully controlled missions in 35 years of business a consolidated mission control approach has evolved. However the mission complexity and the amount of mission products of spacecraft have steadily increased and the use of state-of-the-art technologies is part of continuous improvement policy in ESOC.

In this framework investigations have been carried out on the potential use of Fuzzy Logic (FL) to implement specific applications in support of mission control functions.

2 Mission Control Functions at ESOC

The core activity ESOC is to fly ESA space missions, operating the satellites and ensuring that they meet their mission objectives.

Timely delivery of mission products to the user community (e.g. Universities, Research Centres) satisfying both quantitative and qualitative criteria is a major objective to fulfil. In addition on-board health status has to be monitored and maintained, where possible, up to the level of anticipating the degradation in performance in order to take preventive actions for reconfiguration before on-board automation resets the spacecraft autonomously.

The steady state – routine operations phase, see sect. 2.2 – is characterised by the following operational activities:

- Mission planning, carried out together with the user community and the mission project, to define a feasible plan of spacecraft activities for the next target period, including both payload related activities (e.g. observations, scientific measurements, instrument maintenance) and platform activities (e.g. platform maintenance, orbit manoeuvre).

- Monitoring of real-time on-board status, through visualization of received telemetry parameters, for a quick understanding of the spacecraft health status and on-going activities.
- Control of on-board activities, through uplinking of pre-validated telecommands, derived nominally from the approved mission plan.
- Analysis of spacecraft status evolution, usually done off-line, with stored telemetry and telecommand history data, for the objective of deep understanding of the evolution of the on-board health status to eventually identify upcoming degradation processes.
- Procedures maintenance, to keep up-to-date the complete set of nominal and contingency operational procedures; this activity include the pre-validation of each modified procedure with the available system simulator.
- Training and re-training of operational staff, with use of the system simulator and additional training tools.

2.1 Preparing for a Mission

During the preparation phase a set of coordinated and centrally managed activities are carried out with the objectives of getting everything ready in time to support the launch of the spacecraft. It consists of both requirements definition and implementation of the required infrastructure (hardware and software), maximising the reuse of the existing and available common infrastructure.

The main building blocks of a typical Mission Operations Centre include the Mission Control System, for monitoring and control, the Flight Dynamic System, for attitude and orbit management, the System Simulator, able to simulate the spacecraft functions and the environment, including the ground station communication services, the Data Disposition System, able to provide the users community (e.g. the Science Operations Centre) with up-to-date payload data and the Mission Planning System, to support the planning of the on-board activities (see Fig.1).

The Mission Control System is interfaced with a set of ground stations for supporting the space-ground communication link with the satellite. The Science Operations Centre is the source of payload activity requests and the sink for the generated mission products.

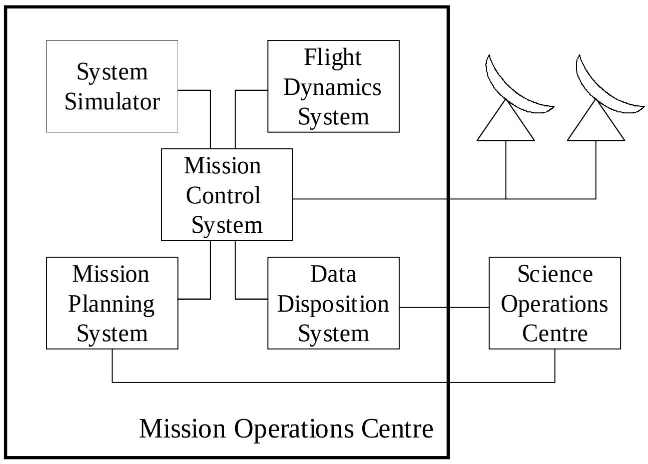

Fig. 1 – A typical mission operations centre with external interfaces

In addition the operational procedures are being prepared and operations personnel is getting trained. While hardware and software, including databases, undergo a thorough acceptance testing, procedures and control personnel are respectively validated and certified during mission control simulation sessions, where both nominal and contingency operations scenarios are simulated with the use of the system simulator.

Several teams are involved, each one with its domain of expertise: flight dynamics, mission control system, ground station and network, flight control, simulation, and site services. Also fundamental is the interaction with the external (to

ESOC) teams, including the mission project, industry and the principal investigators from Universities and research centres.

2.2 Flying a Mission

The launch date is the reference for both mission preparation and mission execution phases. With the launch we have the change of phase.

Mission execution is split in the following sub-phases:

- Launch and early orbit phase (LEOP), the most critical one, encompassing the activation of all the spacecraft's platform subsystems. All activities are rigorously scheduled and little margin – in terms of time – exists for keeping the satellite alive. During this short phase – usually lasting one week – a set of expert teams is available 24 hours a day for supporting any kind of contingency.
- Commissioning phase then follows, which is devoted to the activation and calibration of all on-board payload and experiments. This phase is supported by the flight control team and by the principal investigators, responsible for each individual payload.
- Routine phase is the "productive" phase, when the spacecraft is able to provide the expected mission products to the users community. In this phase we have also (corrective and preventive) maintenance of the spacecraft health status and of the orbit.

2.3 The Challenges of the Future Missions

Upcoming and planned future missions are characterized by an increase of complexity of on-board platform subsystems and by an increased rate of on-board produced experimental data, generated by sophisticated payloads.

Such increase of complexity is reflected in challenging requirements on ground – one example is the need for diagnostic tools of critical or complex units, or an increase of the on-board autonomy level – reflected on ground with an enhanced supervisory function and an adequate on-board software maintenance tool.

Another challenge comes from an overall need to further reduce mission operations costs, yet providing operational services at an acceptable risk level. One way, among others, is to increase the level of automation in specific non critical routine tasks.

3 Fuzzy Logic for What

Given the stated requirements it is natural to investigate matured methods and techniques that might be suitable for the implementation of the aimed improvements.

One peculiar characteristic in the operational world is the refinement of the operational knowledge with the experience. This knowledge, however, is not black and white as it is intimately related to the real world and therefore has an intrinsic imprecision and approximation in its reasoning. What is required, however, in operations, is a clear and precise formulation of what needs to be done given a certain course of events – and the rationale behind it.

This imprecision of expert knowledge reflects what Albert Einstein already stated [2] in 1921: "so far as the laws of mathematics refer to reality, they are not certain. And so far as they are certain, they do not refer to reality".

Fuzzy Logic just seems to be an interesting logic and computing method for analysing the information arising from human cognitive processes [3].

Fuzzy logic control, supervision and fault diagnosis of systems with available quantitative and qualitative knowledge is now a consolidated approach for both normal and special operating conditions [4]

3.1 The Most Promising Application Areas

In operations the introduction of innovative solutions and supporting tools is always carefully scrutinised, particularly in spacecraft operations, where mistakes are not tolerable: once the “bird” is flying there is no way to have it back on ground for repair.

The idea is then to identify improvement areas where the affected implementation might provide a significant enhancement of the performance of the affected function and have, at the same time, the man-in-the-loop to make the last check before commanding.

This translates in the implementation of FL decision support systems to help the operator in areas such as real-time supervision, diagnostics, failures management.

Process optimisation is also another feasible area, for instance, to support optimal task scheduling or optimal battery charging profile.

3.2 Current and Past Implementations

Battery Management

In 1998 initial investigations with FL theory and feasibility analysis were carried out with the implementation of a spacecraft battery management tool [7]. The purpose of this tool was to compare, by means of simulation, the advantages and limits of controlling the process of battery charging respectively comparing a fuzzy logic controller with the traditional threshold limit approach.

The knowledge used in the database was derived from a set of battery performance tests at various environmental conditions.

The results were encouraging, and the simulation with the gradual adjustment of the charging current made possible to reach a longer operational life of the battery. Alternatively for the same mission objective – and mission duration – a smaller battery would have been required, with valuable saving in spacecraft dry mass.

ERS-2 Gyroscope Monitoring

In early 2000 a second fuzzy logic based prototype was implemented for the monitoring of the ERS-2 gyroscopes health status, incorporating the operational knowledge matured so far during past gyroscope failures. 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 and constantly monitored during the duration of the mission.

This study was a test-bed to verify the possibility of FL to incorporate within its inference engine the operational knowledge in analysing, discriminating and detecting an upcoming degradation of an on-board gyroscope, not visible throughout the traditional out-of-limit checking. The implemented model was based on the operational experience of the operations and flight dynamics engineers, while managing past gyroscope failure events.

Early detection of gyroscope degradation is important to anticipate the on-board automatic spacecraft reconfiguration into safe emergency mode, triggered by out-of-limits, which ultimately interrupts any delivery of mission products.

The results, based on real telemetry data, taken from past failure cases, demonstrated the capability of the FL-based tool to recognise the “signature” of the upcoming failure, providing the spacecraft controller with the associated alarm

Ulysses Nutation Anomaly Monitoring

In the second half of 2000 another investigation was carried out to support operations during the Ulysses nutation anomaly season [1].

The objective of the study was to evaluate the benefits of using FL technology to assist the Ulysses flight control team in nutation anomaly monitoring and trend analysis. In addition the application was aimed – in contingency situations – to recommend actions based on past and current operational experience in similar conditions.

The prototype application was installed for evaluation at the Ulysses Mission Control Centre in

JPL, Pasadena, Calif., and represented the first FL application for an ESA mission with automatic data retrieval and processing. It provided the operator with up-to-date nutation anomaly early warning and, when required, suggested the appropriate recovery action. The output – in terms of level of severity and suggested action - was demonstrated reliable and in agreement with the actual control team decisions. The tool was also able to provide early reliable warning, about 5-15 minutes in advance, before implementing the suggested corrective action.

ENVISAT Gyroscope Monitoring

The positive experiences so far reached led to the first operational implementation of a FL-based tool in support of the ENVISAT mission [9], launched in March 2002, to monitor the gyroscope health status and generate early warning of detected performance degradation and possibly anticipating the safety on-board alarming.

This expert system provides the spacecraft controller's team, responsible for satellite operations, with a new type of gyroscope health diagnostic tool. 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, guiding the flight control engineer in the diagnostic process.

The implemented FL model is now embedded in a decision-support system, the ENVISAT Gyroscope Monitoring tool: the ENVISAT flight control team will make extensive use of the tool for regular checking of the on-board gyroscope health status.

PROBA Dynamic Scheduler

This case [5,6], currently in the development phase, consists in the implementation of an automatic re-scheduler of mission tasks for PROBA, based on FL and predicate calculus.

The aim is to have an on-board autonomous system able to update a set of scheduled activities - addressing both platform and payload operations - once internal constraints (e.g. availability of on-board resources, such as memory, stored energy, etc.) changes or a new set of prioritised observation or maintenance tasks are requested.

The problem is treated as a multi-criteria decision making [8] on a dynamic knowledge base of the entire system. A search direction technique is proposed based on different ranking processes on the possible decisions in solving violations. The heuristics that orders and prunes a list of choices is iteratively created through dedicated fuzzy blocks.

The fuzzy logic has been selected to simulate the human behaviour in making decision within complex domains. The activities re-allocation is implemented through the predicate calculus on the knowledge base.

The proposed method gives a final scheduling scenario at a very high level.

4 Lessons Learnt and Expectations

The degree of acceptance of FL based solutions in support of mission control functions is progressively growing within the flight operations community.

The introduction of FL has been facilitated among others by a pragmatic case-based solution-oriented implementation approach: the development of the FL application was regularly monitored and feed-backed by the flight control engineer proposing the case: expertise knowledge transfer was eased by means of frequently focused telecons. The final product was at the end used operationally for its evaluation and eventually to support the flight control team in the specific function. It was confirmed that the case demonstration is less effective than the hands-on experience of the flight control engineer.

In addition the presentation of theoretical background and practical examples, with on-site lectures and workshops hold by Academia and industrial experts has contributed and will contribute to stimulate interest and awareness of the potentiality of FL in several application domains.

A generic case-based approach to facilitate the introduction of mature and innovative technology for mission control functions has been derived from the experience related to FL technology and is reported in Fig. 2.

For future applications it is envisaged to explore benefits from synergy between FL and other soft computing technologies such as genetic algorithms and artificial neural networks.

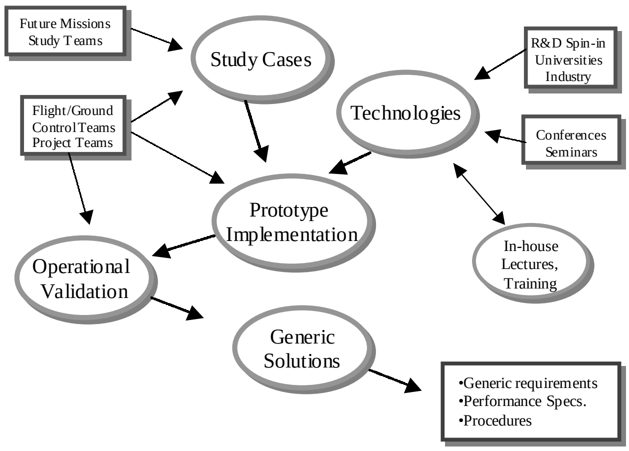

Fig. 2- Approach for the introduction and use of case-based innovative solutions using suitable available technologies.

An area requiring further improvement is the effective capturing of the available operational knowledge in a low-cost, non-intrusive manner.

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