An implementation of a satellite simulator as a fuzzy rule-based inference machine

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Abstract. *This work describes how a satellite simulator, intended for verification and approval of satellite operations plans, can be implemented by means of a fuzzy rule-based expert system. First, the satellite operations planning process is briefly explained, after a hypothetical mission operation scenario. A set of simple control rules, devised specifically to deal with this scenario, is then presented. It is shown that these rules can be easily updated for application to actual satellite operations plans, after some minor adjustments.*

1. Introduction to satellite operations planning

The process of designing, assembling, and launching artificial satellites is a very costly one. However such an endeavor can be justified, as long as the satellite successfully performs the mission operations for which it was conceived, for the amount of time for which it was designed.

A satellite operation planning, as the name implies, consists on planning ahead procedures to be executed on the satellite, in order for it to perform mission operations. The procedures must be scheduled in such a way that either quantity or quality of mission operations is maximized, if not both of them. Because of inherent uncertainties associated to future predictions, this roughly translates into successively optimizing operations in a fixed timeframe. This must be done while eliminating altogether, or at least minimizing, actions that might result in degradation of onboard equipment.

In order to perform a successful satellite operations planning, one must fulfill as many requirements as possible, while observing all existing constraints. The requirements differ according to each mission, and may even change over time for the same mission. For example, in some data collection applications, it might be important to routinely gather as much data as possible over a specific set of targets, in order to monitor how they change over time. For other applications, users might want to study specific events, which occurrences should not be missed. Sometimes, unique opportunities might call for operations for which the mission was not specifically designed. Usually such specific operations will be attempted in addition to the routine operations, unless the evaluation of constraints reveals this to be impossible. In this case, the scarcity of data availability might dictate that the unique operation should take precedence over routine data collection. Or the contrary might happen, if the loss of routine data caused by this procedure deviation is shown to reach unacceptable levels. In such cases, conflict management must be performed. The prioritization of operations is usually documented at the design phase, or decided ad hoc by the mission center. Alternatively, it could be performed as a joint work with information exchange between the mission center and the operations planning.

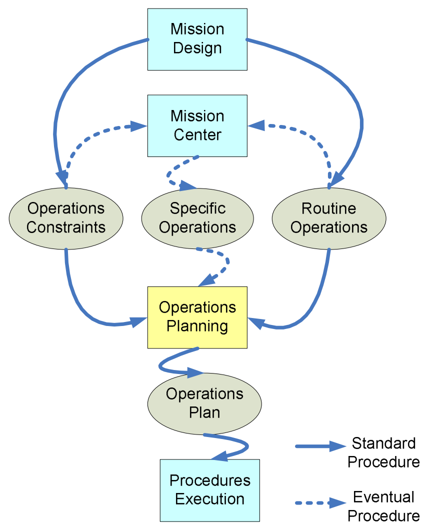

Figure 1. A typical satellite operations planning architecture

A perfect mission design would allow the spacecraft to fulfill any mission operation request, without restrictions. A good design will allow most of them, most of the time. A perfect operations planning would fulfill all possible mission operation requests within a given set of constraints. A good planning will execute most of them, while observing all of the constraints. In order to better illustrate how operations planning works, a hypothetical mission operations scenario will be presented and explained in the following section.

2. A hypothetical mission operations scenario

2.1. Mission overview

The primary objective of the XSAT mission is the continuous monitoring of the Brazilian Amazon region. For this purpose, the XSAT spacecraft is equipped with an optical camera (PL1) for deforestation monitoring, plus a data collection transponder (PL2) for relaying environmental data acquired by data collection platforms.

PL1, the optical camera payload, is primarily designed for daytime land imaging. Nighttime imaging over the ocean could be performed, but only for calibration purposes. This calibration may be performed once early in the satellite lifetime, or on demand as requested by the mission center. Image data acquired by this payload is transmitted at real-time to an image receiving station (IRS), while the spacecraft is within its visibility range. The image data transmitter consumes a very high amount of power while operating ($P_{PL1}(ON)$ = 800 W; $P_{PL2}(OFF)$ = 100 W). This may damage the satellite and shorten its lifetime. Therefore, this payload must be powered on only when the satellite approaches the image receiving station, and powered off once the satellite leaves.

PL2, the data collection payload, receives environmental data from autonomous platforms located at remote locations, either on ground or afloat, and retransmits them to data collection stations. These platforms may be located deep in the jungle, or float over buoys on the ocean, transmitting data at fixed intervals toward the sky. Any such signal received by the satellite is immediately retransmitted to the ground, to be caught by a data collection station (DCS), if available. For optimal power management, the payload must be operated in the visibility range of data collection stations. However, as the power consumption of this payload is very low (P_{PL2}(ON) = 15 W; P_{PL2}(OFF) = 5 W), it can be kept powered on continuously.

Both payload data transmitted from the satellite are received at data receiving stations on ground, and then forwarded to data processing centers, also on ground. For improved performance, the locations of data receiving stations must be chosen according to the satellite orbit. Data processing centers do not follow this restriction.

2.2. Orbit description

The XSAT orbit is equatorial, with zero degrees inclination. This means that the flight path of the satellite is located directly above the Earth equatorial line. This orbital configuration confines the satellite passes to the equatorial region. But for a mission designed to monitor the Amazon, using data receiving stations located near the equatorial belt, this orbit maximizes the amount of payload data exchanged during the satellite lifetime.

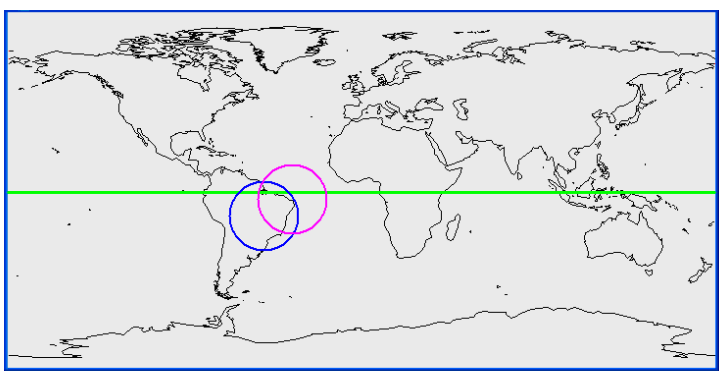

Figure 2. XSAT orbit path and visibility ranges of data receiving stations

XSAT operates at low Earth orbit. At its design orbit altitude, the satellite performs 14.4 revolutions per day. In other words, it completes an orbital revolution cycle around the Earth once every 100 minutes. Because the orbit is also equatorial, the satellite will be visible from data receiving stations once every orbit, about 14 times per day.

At about one third of the time of an orbit cycle, the satellite will be in the Earth shadow, seen from the Sun. It is then said to be at eclipse. At the remaining two thirds of the time, the satellite will be illuminated by sunlight. For the satellite to generate power, it must be in sunlight. At eclipse, energy becomes a scarce resource that must be carefully managed. Therefore, PL1 operates mostly when the satellite is in sunlight, while PL2 is expected to provide data in both sunlight and eclipse.

Table 1. XSAT mission operations summary

Payload	Description	Payload data	Data receiving station	Operation criteria	Power Consumption
PL1	Optical Camera	Satellite imagery for land surface monitoring	Image receiving station	Over station, usually at sunlight	High ON = 800 W OFF = 100 W
PL2	Data Collection Subsystem	Environmental data acquired by data collection platforms	Data collection station	Over station or continuous, at sunlight and eclipse	Low ON = 15 W OFF = 5 W

3. Spacecraft power supply modeling

The satellite platform must provide all the necessary conditions for the proper operation of the payloads. This includes providing the electrical power consumed by the payloads module, plus also by the platform service module (SM). To fulfill this requirement, XSAT is equipped with a pair of rotating solar panels comprising the solar array generator (SAG), and a rechargeable battery unit (BAT).

In the illuminated phase, the SAG generates electric energy from sunlight. Under this condition, the solar panels will rotate continuously to track the Sun, so that the power output remains constant throughout the illuminated phase (P_{SAG} = 1600 W). When the satellite exits sunlight, the power output of the SAG drops to zero.

At eclipse, the BAT is responsible for the generation of all electrical energy spent onboard. Even with all payloads inactive, the satellite platform service module must remain powered on (P_{SM} = 780 W), and the payloads consume a small amount of power to keep it at standby (P_{PL1}(OFF) + P_{PL2}(OFF) = 105 W). The BAT will thus discharge continuously until the end of eclipse, when recharging begins. Early in sunlight, the power used by the satellite is generated by the SAG. The surplus energy is directed to the BAT, recharging it. Once the BAT is fully charged, this process is interrupted to avoid damage by overcharge.

Another factor that is known damage a battery is excessive discharge. In order to avoid this, the depth of discharge (DOD) must be kept low. In XSAT, a DOD above 15% must be avoided, and a value as high as 20% is strictly forbidden.

3.1. The battery charge model

The maximum charge capacity (Q_{MAX}) is a design parameter for most rechargeable batteries, and is usually expressed in ampere-hours (Ah).

The recharge ratio (η_{CD}) is another battery design parameter. It represents the amount of energy stored into a battery divided by the energy retrieved from it. A recharge ratio of one is expected form an ideal battery.

The battery full charge voltage (V_{MAX}) is the maximum voltage that the battery is allowed to reach until the charging process is interrupted. The battery voltage increases with charge, and decreases with discharge. By considering the battery analogous to a capacitor, one can estimate the battery capacitance (C_{BAT}) from the full charge voltage and the maximum charge capacity ($C_{BAT} = Q_{MAX} / V_{MAX}$).

Table 2. BAT design parameters

Parameter	Symbol	Nominal Value
Maximum Charge Capacity	Q_{MAX}	**60 Ah**
Recharge Ratio	η_{CD}	**1.1**
Full Charge Voltage	V_{MAX}	**52 V**
Estimated Battery Capacitance	C_{BAT}	**1.2 Ah/V**

The DOD is obtained by dividing the battery discharge by its maximum charge capacity (Q_{MAX}). The battery discharge is the complement of its internal charge (Q_{BAT}) with regard to the maximum charge (Q_{MAX}). Therefore, the DOD can be expressed as a function of the internal charge and the maximum charge capacity ($Q_{BAT} = 1 - Q_{BAT} / Q_{MAX}$). The internal charge ($Q_{BAT}$) is obtained by integrating (or summing, in discrete calculus) the battery current (I_{BAT}) over the time. While discharging, the batter charging power (P_{BAT}) divided by the battery voltage (V_{BAT}) gives the battery current value ($I_{BAT}(CHG) = P_{BAT} / V_{BAT}$). When discharging, the recharge ratio must be taken into account ($I_{BAT}(DIS) = \eta_{CD} * P_{BAT} / V_{BAT}$). In both cases, the battery voltage is obtained by dividing the internal charge by the battery capacitance ($V_{BAT} = Q_{BAT} / C_{BAT}$). If the battery is full, the battery current is cut ($I_{BAT}(FULL) = 0$).

Table 3. DOD evaluation parameters summary

Parameter	Symbol	Expression
Depth of Discharge	**DOD**	$1 - (Q_{BAT} / Q_{MAX})$
Battery Internal Charge	Q_{BAT}	$\Sigma_T I_{BAT} * \Delta T$
Battery Current	I_{BAT}	$I_{BAT}(CHG) = P_{BAT} / V_{BAT}$
		$I_{BAT}(DIS) = \eta_{CD} * P_{BAT} / V_{BAT}$
		$I_{BAT}(FULL) = 0$
Battery Voltage	V_{BAT}	Q_{BAT} / C_{BAT}

The battery power (P_{BAT}) at every instant can be evaluated from the power available to the satellite (P_{AV}). The difference between the power generated by the SAG and the power consumed by the satellite as a whole is the available power (P_{AV}). If the available power is negative, the battery must supply the difference ($P_{BAT}(DIS) = P_{AV}$). If the available power is positive, the battery will be charged ($P_{BAT}(CHG) = P_{AV}$), until it reaches full charge. At this point, the battery power becomes zero ($P_{BAT}(FULL) = 0$).

Table 4. XSAT onboard power budget

Operation Mode	Onboard Status				Power (W)		
	SAG	PL1	PL2	SM	Consumed	Generated	Available
A	SUN	ON	ON	-	1595	1600	5
B	SUN	ON	OFF	-	805	1600	795
C	SUN	OFF	ON	-	115	1600	1485
D	SUN	OFF	OFF	-	885	1600	715
E	ECL	ON	ON	-	1595	0	-1595
F	ECL	ON	OFF	-	1585	0	-1585
G	ECL	OFF	ON	-	895	0	-895
H	ECL	OFF	OFF	-	885	0	-885

The available power depends on the operation mode, which changes according to the onboard status. The onboard status defines power generation and consumption.

Table 5. XSAT power figures

Onboard Status		Description	Generated Power (W)	Consumed Power (W)
SAG	SUN	Sunlight	1600	0
	ECL	Eclipse	0	0
PL1	ON	PL1 Operating	0	800
	OFF	PL1 Standby	0	100
PL2	ON	PL2 Operating	0	15
	OFF	PL2 Standby	0	5
SM	-	Service Module	0	780

The onboard status of payloads can be changed by means of time-tagged on/off telecommands. The onboard status of the SAG depends on the satellite orbit position. The execution time of telecommands is decided by the operations planning, whereas the satellite orbit position is estimated by the flight dynamics.

The DOD depends on the satellite operation mode and the battery charge mode, affecting the way the payloads can be operated. This type of relationship can be represented by a set of logical control rules, which can be used as a basis for an inference machine.

4. Implementation of a satellite simulator as an inference machine

4.1. XSAT simulation control rules

The routine operation requirements of XSAT can be obtained from the mission operations description in the second section. They are presented in the following table.

Table 6. XSAT requirements control rules

IF (DCS = VISIBLE) THEN (PL1 = ON)
IF (DCS != VISIBLE) THEN (Decide whether(PL1 = OFF))
IF ((IRS = VISIBLE) AND (SUN = TRUE)) THEN (PL2 = ON)
IF ((IRS = VISIBLE) AND (SUN = FALSE)) THEN (Decide whether(PL2 = ON))
IF (IRS != VISIBLE) THEN (PL2 = OFF)

In the rules above there are some decision points regarding payloads operation, more specifically dealing with PL2 calibration and PL1 power off. They must take into account the DOD, as seen in the third section. The DOD evaluation rules are shown below.

Table 7. XSAT DOD evaluation control rules

IF (SUN = TRUE) THEN (P_{SAG} = 1600 W)
IF (SUN = FALSE) THEN (P_{SAG} = 0 W)
IF (PL1 = ON) THEN (P_{PL1} = 800 W)
IF (PL1 = OFF) THEN (P_{PL1} = 100 W)
IF (PL2 = ON) THEN (P_{PL2} = 15 W)
IF (PL2 = OFF) THEN (P_{PL2} = 5 W)
IF (TRUE) THEN (P_{SM} = 780 W)
IF (TRUE) THEN ($P_{AV} = P_{SAG} - (P_{PL1} + P_{PL2} + P_{SM})$)
IF ($P_{AV} < 0$) THEN (BAT = DIS)
IF (($P_{AV} > 0$) AND ($Q_{BAT} < Q_{MAX}$)) THEN (BAT = CHG)
IF (($P_{AV} > 0$) AND ($Q_{BAT} = Q_{MAX}$)) THEN (BAT = FULL)
IF (BAT = FULL) THEN (P_{BAT} = 0 W)
IF (BAT != FULL) THEN ($P_{BAT} = P_{AV}$)
IF (TRUE) THEN (C_{BAT} = 1.2 Ah/V)

Table 7. XSAT DOD evaluation control rules (continued)

IF (TRUE) THEN (V_{MAX} = 52 V)
IF (TRUE) THEN (η_{CD} = 1.1)
IF (TRUE) THEN (Q_{MAX} = 60 Ah)
IF (TRUE) THEN ($V_{BAT} = Q_{BAT} / C_{BAT}$)
IF (BAT = CHG) THEN ($I_{BAT} = P_{BAT} / V_{BAT}$)
IF (BAT = DIS) THEN ($I_{BAT} = \eta_{CD} * P_{BAT} / V_{BAT}$)
IF (BAT = FULL) THEN (I_{BAT} = 0 A)
IF (TRUE) THEN ($Q_{BAT} = Q_{BAT} + I_{BAT} * \Delta T$)
IF (TRUE) THEN (DOD = 1 - Q_{BAT} / Q_{MAX})

The DOD evaluation must be performed iteratively, as its instant value recursively depends on the past value of the internal charge (Q_{BAT}). In calculating the DOD for a given timeframe, we are essentially simulating the satellite power supply. It must be also noted that the DOD must be calculated continuously for the timeframe under evaluation plus an additional margin period, in order to make sure that a past operation will not bring catastrophic results sometime in the future. Based on the maximum value of the DOD thus evaluated, one can decide as to how the payload must be operated.

Table 8. XSAT operation decision based on DOD

IF ((DOD <= 15%) THEN (Operation Safe)
IF ((DOD > 15%) AND (DOD < 20%)) THEN (Operation Dangerous)
IF (DOD >= 20%) THEN (Operation Forbidden)

According to the decision criteria above, there are still some doubts as to what should be exactly done when the DOD has an intermediate value between 15% and 20%. One simple solution for this dilemma would be the delineation of limits by the application of fuzzy logic, by defining LOW and HIGH conditions for the DOD to be pondered.

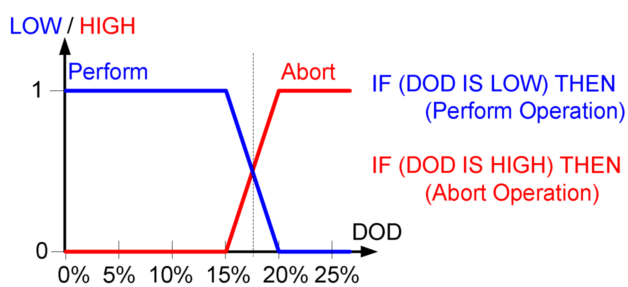

Figure 3. An example of fuzzy conditions based on evaluated DOD

4.2. Building the simulator

A rule-based fuzzy inference machine that can work as the simulator proposed is already available. It was built as a validating tool for satellite flight operations plans, to be generated by a new operations planning system currently under development at INPE.

In order for this simulator to operate, one must supply the events queue and the initial internal state. The events queue can be easily obtained from decoding the flight operations plan. This process if performed by an events preprocessor software application. An events preprocessor application built specifically for the CBERS-2B satellite is already available.

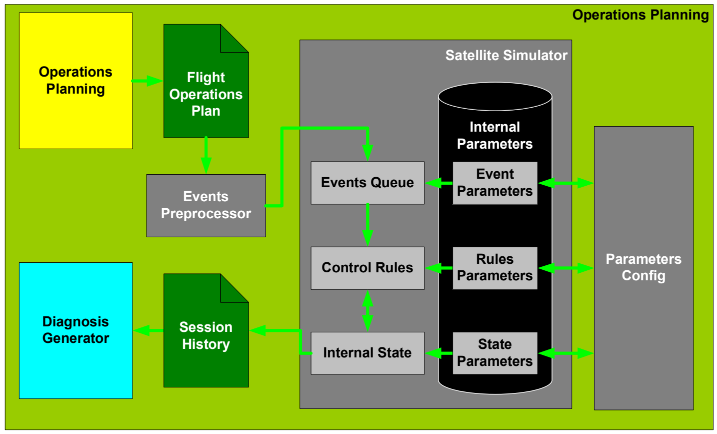

Figure 4. Operations planning validation architecture

5. Extending this work to actual missions

5.1. SCD

The SCD (Data Collection Satellite) is a family of spin-stabilized satellites developed under the MECB (Complete Brazilian Space Mission) program. SCD1 was launched in 1993, and SCD2 in 1998. These satellites have a single payload that is very similar to the PL2 presented for XSAT. Both have attitude angle maintenance requirements that must be fulfilled through the execution of attitude maneuvers, although the angle limits differ slightly for each satellite. These maneuvers are performed by the activation of magnetic torquers, which must operate continuously for several orbit revolutions for the desired result. The power consumption pattern during such maneuvers could be modeled as that of a payload with special operation requirements. The porting of such an operation scenario to the XSAT simulation model would be straightforward.

5.2. CBERS

The CBERS (China Brazil Earth Resources Satellite) is another family of satellites operated by INPE. CBERS1 was launched in 1999, CBERS2 in 2003, CBERS2B in 2007. CBERS3 is expected to be launched in 2012. These satellites have a set comprising from six to eight payloads. Two of them are environmental data collectors, one of them being identical to the SCD payload. The remaining payloads are optical cameras and associated equipment, similar to the PL1 of XSAT. By adding more onboard statuses, it would be possible to simulate these satellites using the XSAT simulation model as a template.

5.3. AMAZONIA

The AMAZONIA is a planned family of satellites intended to complement the CBERS satellites in obtaining Earth images. The payload configuration of these satellites should be the most resembling to the XSAT.