KONGR45GPEN

# DESIGN OF FAULT DETECTION, ISOLATION AND RECOVERY IN THE ACUBESAT NANOSATELLITE

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The AcubeSAT project is carried out with the support of the Education Office of the European Space Agency, under the educational Fly Your Satellite! programme.



*First printing, 2021*

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# *Acronyms*

*ADCS* Attitude Determination and Control Subsystem . . . . . . . 15, 16

*CCSDS* The Consultative Committee for Space Data Systems . . . . 15

*CDR* Critical Design Review . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 15

*COMMS* Communications . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 15, 16

*COTS* Commercial Off-The-Shelf . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 16

*ECSS* European Cooperation for Space Standardization . . . . . . . . . . 21

*EMC* Electromagnetic Compatibility . . . . . . . . . . . . . . . . . . . . . . . . . . . 16

*EPS* Electrical Power Subsystem . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 16

*FDIR* Fault Detection, Isolation and Recovery . . . . . . . . . . . . . . . . . . . . 25

*FDIR* Fault Detection, Isolation and Recovery . . . . . . . . . 13, 15, 21, 23

*GS* Ground Station . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 16

*ISM* Industrial, Scientific, Medical . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 16

*LEO* Low Earth Orbit . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 18

*MPPT* Maximum Power Point Tracking . . . . . . . . . . . . . . . . . . . . . . . . . 16

*OBC* On-Board Computer . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 16

*OBDH* On-Board Data Handling . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 17

*OPS* Operations . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 17

*PA* Product Assurance . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 15

*PCDU* Power Conditioning & Distribution Unit . . . . . . . . . . . . . . . . . . 16

*PDMS* Polydimethylsiloxane . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 19

*PUS* Packet Utilisation Standard . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 21

*RF* RadioFrequency . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 15, 21

*SU* Science Unit . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 16, 18

*SYE* Systems Engineering . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 18

*TC* Telecommands . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 15, 21

*TM* Telemetry . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 15

*UHF* Ultra-High Frequency . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 16, 18

# *Abstract*

Space is not a welcoming environment; while the aerospace engineering community has managed to reliably operate thousands of satellites in orbit, CubeSats, the most popular class of nanosatellite, only have a 50% success rate. Low costs, lack of strict technical requirements and scarcity of publicly available documentation often drives up the risks for educational, scientific and commercial CubeSats. This thesis investigates a configurable and modular Fault Detection, Isolation and Recovery (FDIR) architecture that uses the ECSS Packet Utilisation Standard. This FDIR concept, along with the provided open-source software implementation, can be used by CubeSat missions to increase the reliability of their design and chances of mission success, by autonomously responding to on-board errors. The thesis also includes background information regarding CubeSat reliability, and explores the software and hardware used to implement the proposed FDIR design on the AcubeSAT mission, currently under design by students of the Aristotle University of Thessaloniki.

KAPOU EDW tha mpei kai to abstract sta ellhnika

# 1
# *Reliability Engineering in CubeSat Systems*

## *1.1 Kalispera*

space is very important[1] Fault Detection, Isolation and Recovery (FDIR)

[1] Durou, Godet, Mangane, Pérarnaud, and Roques, "Hierarchical Fault Detection, Isolation and Recovery Applied to Cof and Atv Avionics."

# 2
# *The AcubeSAT mission*

## 2.1 *CubeSat*

## 2.2 *Subsystems*

The AcubeSAT nanosatellite is technically and programmatically split into N different subteams or **subsystems**, each responsible for a different se[1]ction of the satellite, and made up out of M dedicated members.

In the following sections, a brief introduction on the function and design of each subsystem is presented. As the Systems Engineering and Product Assurance process is inherently connected to the function of all subsystems, the details relevant to FDIR are also mentioned. For more detailed information, the reader is encouraged to refer to AcubeSAT's website[2], or to the publicly available Critical Design Review (CDR) documents[3].

[1] White, Shields, P. Papadeas, Zisimatos, Surligas, Papamatthaiou, D. Papadeas, and Kosmas, "Overview of the Satellite Networked Open Ground Stations (SatNOGS) Project."

[2] `https://acubesat.spacedot.gr/subsystems/`

[3] `https://gitlab.com/acubesat/documentation/cdr-public`

### 2.2.1 *Attitude Determination and Control Subsystem (ADCS)*

### 2.2.2 *Communications (COMMS)*

The communications subsystem is responsible for transmitting data between the Earth and the spacecraft in orbit. The transmitted data is split into 3 different categories:[4]

- **Telecommands (TC)**: Commands from the Earth to the satellite. They can be used to request information, or to perform specific spacecraft actions.
- **Telemetry (TM)**: Information sent from the satellite towards Earth, typically including vital information such as sensor values, system status, timestamps and events.
- **Science data**: The scientific data generated by the payload. These are the highest-volume data and represent the main scientific output of the mission.

It is important to mention that the satellite orbit only allows for a very short visibility duration every day, increasing the needs for on-board autonomy and the importance of a correctly implemented FDIR method.

[4] Kapoglis and Chatziargyriou, *AcubeSAT TTC DDJF*.

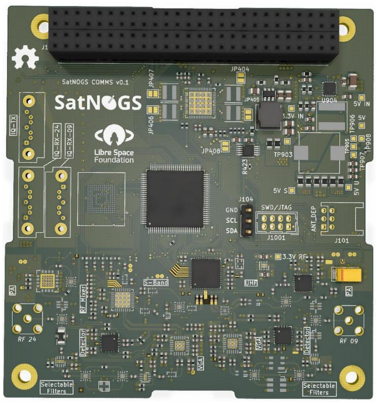


Figure 2.1: The SatNOGS COMMS board.

The main component of the COMMS subsystem is the **SatNOGS COMMS board**,[5] an open-source RF transceiver developed by the LibreSpace Foundation, based on CCSDS telecommunications standards.

[5] Surligas, "SatNOGS-COMMS."

Communication will take place using 2 frequency bands on the ISM range, namely 436.5 MHz and 2.425 GHz, supported by a deployable turnstile and a directional patch antenna respectively. The use of ISM frequencies allows easy radio-amateur access to the satellite. The first (UHF) band also emits a periodic **beacon**, listing information about satellite status.

The communications subsystem is also responsible for the Electromagnetic Compatibility (EMC) analysis and interference mitigation, as well as the design and construction of the satellite Ground Station. The Ground Station will be part of **SatNOGS**,[6] a global network of satellite ground stations based on open technologies and open data.

[6] White, Shields, P. Papadeas, Zisimatos, Surligas, Papamatthaiou, D. Papadeas, and Kosmas, "Overview of the Satellite Networked Open Ground Stations (SatNOGS) Project."

### 2.2.3 *Electrical Power Subsystem (EPS)*

The EPS is the subsystem responsible for the generation, distribution and storage of electrical power of the spacecraft. It is a critical aspect of the spacecraft due to the direct dependence of all subsystems to the high power needs of many CubeSat subsystems, and is theorised to be the most common reason for CubeSat failure.[7]

AcubeSAT has opted for a Commercial Off-The-Shelf (COTS) subsystem approach for the EPS:[8]

[7] Langer and Bouwmeester, "Reliability of CubeSats – Statistical Data, Developers' Beliefs and the Way Forward."

[8] Anastasios-Faidon, Kanavouras, and Pavlakis, *AcubeSAT System DDJF*.

- **Solar panels** are procured from EnduroSat. Four 3U panels cover the $X$ and $Y$ faces of the satellite, and one 1U panel covers the $-Z$ face.
- The **Power Conditioning & Distribution Unit (PCDU)** is procured from NanoAvionics and offers 10 switched channels with overcurrent protection over 4 voltage rails, as well as 4 Maximum Power Point Tracking (MPPT) converters.
- The **battery pack**, also procured from NanoAvionics, contains 4 18650 Li-Ion cells in a 2S2P[9] configuration.

[9] 2 series, 2 parallel

A dynamic approach is taken with regards to power budget calculation:

1. The in-orbit power generation is calculated for the duration of the mission using the **STK** software, taking into account satellite orientation, pointing profiles and eclipse, with a 1 min resolution.
2. The power consumption of the system is calculated on average for each different operational mode.
3. MPPT efficiencies and battery charge level are calculated for each timepoint, assuming worst-case thermal and electrical conditions
4. A system-wide 10% margin is applied to the results

Table 2.1: AcubeSAT nominal mode power budget

| Consumer | Power |
|---|---|
| ADCS | 1.10 W |
| COMMS | 0.85 W |
| EPS | 0.99 W |
| OBC | 0.12 W |
| SU | 0.25 W |
| Total | 3.30 W |
| Orbit Average Power | 4.24 W |

We have created a Python library consolidating the above steps[10] and producing the necessary outputs to prove the adequacy of the design.

[10] https://gitlab.com/acubesat/eps/power-budget

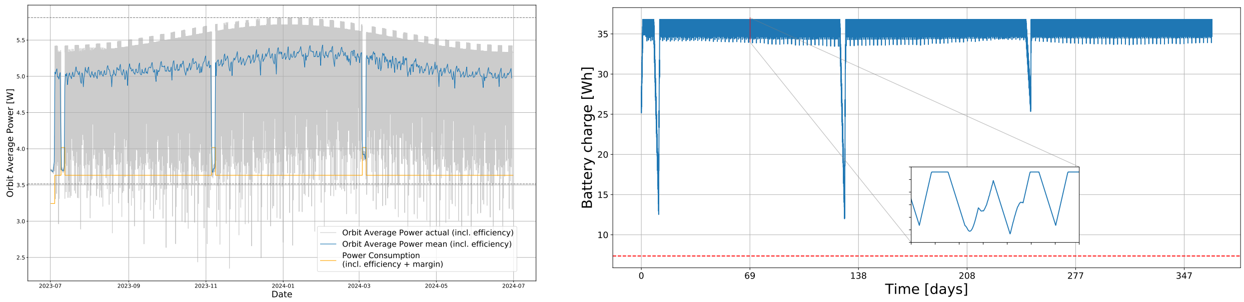


Figure 2.2: Dynamic power budget analysis. Left: Power consumption & generation for the orbit. Right: Battery discharge level throughout the mission

### 2.2.4 *On-Board Data Handling (OBDH)*

### 2.2.5 *Operations (OPS)*

The operations subsystem is responsible
the following system modes:[11]

[11] Zaras, Kapoglis, Georgousi, Papafotiou, Chadolias, Anthopoulos, Retselis, Arampatzis, Xenos, and Christidou, *AcubeSAT Mission Description & Operations Plan*.

- **Launch/Off mode**: During this mode, the satellite is turned completely off, and no subsystems are energised. This is used to represent the state of the spacecraft inside the deployer, where no electronics are allowed to be energised,[12] and the CubeSat is in a completely dormant state.

[12] California Polytechnic State University, *CubeSat Design Specification Rev. 13*, req. 3.3.3.

- **Commissioning mode**: This mode is initiated as soon as the CubeSat exits the deployer, meaning that launch is complete. It contains the initial startup actions of the spacecraft, including detumbling and antenna deployment. No science takes place during commissioning mode.

- **Nominal mode**: This mode represents the state where the CubeSat will spend most of the time on. Apart from the necessary autonomy functions and battery charging, the CubeSat will also downlink telemetry and science data. No science takes place during nominal mode, except for health checks commanded from the ground. Nominal mode is also the only mode where the satellite performs nadir or sun pointing (Section 2.2.1).

- **Science mode**: This is where the main experiment takes place and payload data are generated. This mode includes operation of the fluidic system, control of the microfluidic chip, reinvigoration of the cells, and periodic acquisition of pictures using the miniaturised microscope.

  AcubeSAT has split science mode into **3 distinct occurrences**, termed sub-experiments $\alpha$, $\beta$ and $\gamma$, lasting 72 hours each, and taking place at different points of the mission to investigate the time-dependence of the observed results.

- **Safe mode**: It is common for spacecraft systems to include a *safe mode*,[13] where the spacecraft switches off all non-essential systems and function, in order to respond to major malfunctions that cannot be corrected by autonomous procedures. Safe mode is intended as a well-defined and well-tested mode which is easy to maintain and reduces risk of any malfunction.

  On AcubeSAT, spacecraft functionality is significantly reduced, and the attitude profile includes pointing only. However, UHF communication and beacon transmission are still active for observability purposes.

[13] Aguirre, *Introduction to Space Systems*, p. 385.

| Function | Launch | Commissioning | Nominal | Science | Safe |
|---|---|---|---|---|---|
| ADCS | Off | Detumbling | Pointing | Detumbling | Detumbling |
| COMMS | Off | UHF only | UHF and S-Band | UHF only | UHF only |
| EPS | Off | On | On | On | On |
| OBC | Off | On | On | On | On |
| SU | Off | Off | Maintenance & data only | On | Maintenance only |

Table 2.2: Overview of AcubeSAT functionality on different modes.

Each mode is associated with a **functional flow** diagram, showing a high-level description of the spacecraft operation during this mode.[14]

[14] *AcubeSAT Functional Architecture*.

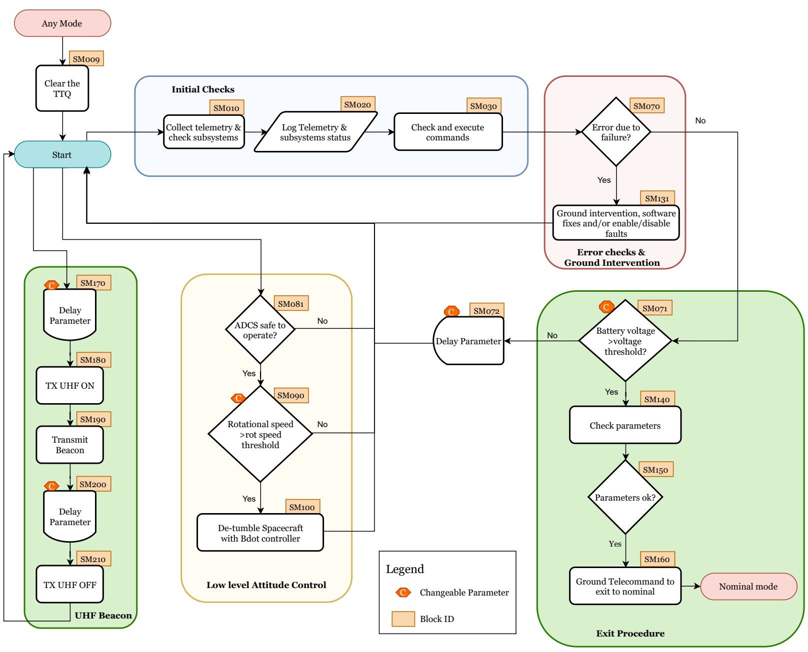


Figure 2.3: Safe mode functional flow

### 2.2.6 *Structural*

### 2.2.7 *Systems Engineering (SYE)*

### 2.2.8 *Science Unit (SU)*

The Science Unit subteam is responsible for the conceptualisation and implementation of the mission's scientific payload, namely the high-throughput study of the effects of Low Earth Orbit (LEO) environments on yeast cells.

The payload is composed of the following functional parts:[15]

[15] Arampatzis, Zaras, Matsatsos, Ousoultzoglou, Nikolopoulou, and Sandaltzopoulou, *AcubeSAT Payload DDJF*.

- A **microfluidic chip** based on Polydimethylsiloxane (PDMS), hosting 384 d

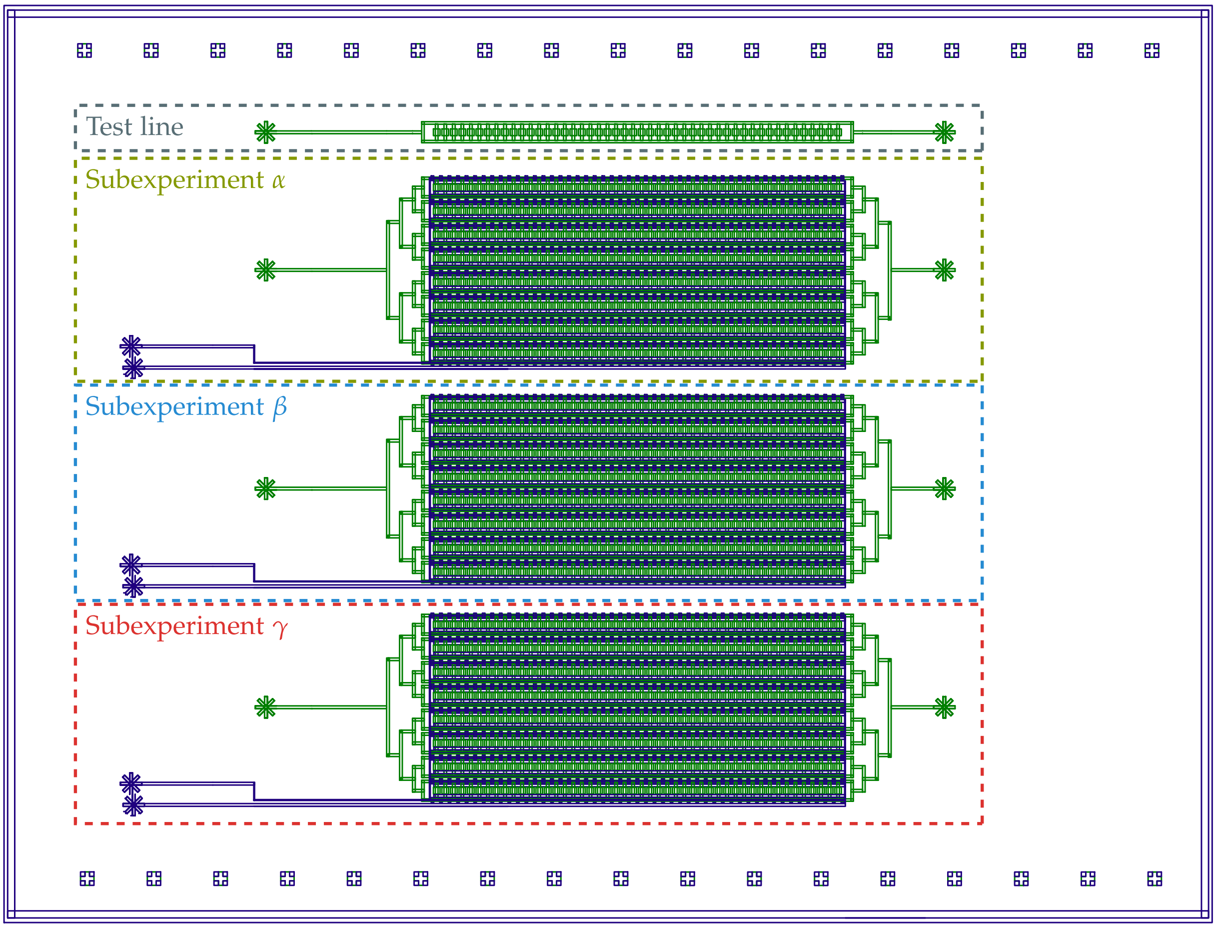


Figure 2.4: The microfluidic chip and its separation into 3 subexperiments and 1 test line. The fluid inlets are shown on the left side of the chip, while the outlets are on the right. *Green:* flow layer. *Blue:* control layer.

### 2.2.9 *Thermal*

### 2.2.10 *Trajectory*

## 2.3 *Tools used*

# 3
# FDIR concept in AcubeSAT

## 3.1 The ECSS Packet Utilisation Standard

### 3.1.1 The ECSS services

TODO

Figure 3.1: The PUS data transfer model

blablablab[1]

- **`ST[01]`: Request verification**

  Provides acknowledgement or failure reports for executed commands. This service essentially informs the operators about the status of TC sent to the spacecraft, and reports any occurred errors during parsing or execution.

- **`ST[02]`: Device access**

  Allows toggling, controlling and reconfiguring any on-board peripherals that do not support the PUS paradigm, but rely on simpler protocols to communicate.

- **`ST[03]`: Housekeeping**

  Produces periodic reports containing values of on-board parameters. This service essentially composes the periodic RF **beacon** of the satellite, by storing and transmitting parameter values without any prior TC request.

- **`ST[04]`: Parameter statistics reporting**

  Allows reporting statistics (min, max, mean, standard deviation) for specific parameters over specified intervals. This is a memory-efficient alternative to the `ST[03]` housekeeping service.

- **`ST[05]`: Event reporting**

  Generates reports when notable occurrences take place on-board, such as:

  - Autonomous on-board actions
  - Detected failures or anomalies
  - Predefined steps during an operation

[1] ECSS Secretariat, *ECSS-E-ST-70-41C – Telemetry and Telecommand Packet Utilization*; ECSS Secretariat, *ECSS-E-70-41A – Telemetry and Telecommand Packet Utilization*; Kaufeler, "The ESA Standard for Telemetry and Telecommand Packet Utilisation."

- **`ST[06]`: Memory management**

  Allows writing and reading directly from an on-board memory unit. This can be useful for debugging and investigative purposes, fetching mission data, or uploading new software to the spacecraft avionics. The service also provides for downlinking and uplinking files in a file system.

- **`ST[07]`: Task management** *(deprecated)*

  Allows stopping, suspending or resuming software tasks in case of contingency. This service has been removed from the standard and is only mentioned as a reference.

- **`ST[08]`: Function management**

  Provides the capability of running predefined actions that can receive further parameters. These actions can correspond to payload, platform, or any other functionality.

- **`ST[09]`: Time management**

  Allows periodic reporting of the current absolute spacecraft time for observability and correlation purposes.

- **`ST[10]`: Time packet** *(deprecated)*

  Used in the past for time packet generation. This service has been removed from the standard and is only mentioned as a reference.

- **`ST[11]`: Time-based scheduling**

  Allows the operators to **"time-tag"** telecommands for execution at future timestamps, instead of immediately.

- **`ST[12]`: On-board monitoring**

  This service allows checking parameter values to ensure that they remain within configurable limits. Whenever a violation occurs, an `ST[05]` can be optionally generated for further processing.

- **`ST[13]`: Large packet transfer**

  Provides a method of message segmentation, for message payloads that are too large to fit within the maximum allowed length for TC or TM.

- **`ST[14]`: Real-time forwarding control**

  This service is responsible of controlling which types of generated reports are immediately transmitted to the Ground Station.

- **`ST[15]`: On-board storage and retrieval**

  This service allows storing generated report on-board, as well as their commanded mass retrieval when the spacecraft has Ground Station visibility.

- **`ST[16]`: On-board traffic management** *(deprecated)*

  Allows monitoring the status and load of an on-board data bus and provides commands for resolution of errors. This service has been removed from the standard and is only mentioned as a reference.

- **`ST[17]`: Test**

  This service allows performing on-board connection and "are-you-alive" checks.

- **`ST[18]`: On-board operations procedure**

  Allows loading, controlling (start, suspend, resume, abort) and configuring On-Board Control Procedures, which are sequences of commands written in an application-specific language.

- **`ST[19]`: Event-action**

  Provides the operators with the capability of autonomously executing TCs when an `ST[05]` event is triggered.

- **`ST[20]`: On-board parameter management**

  Provides the capability of reading and setting on-board parameters. Parameters are some of the most important entities defined in the PUS, and can represent:

  – Read-write configuration variables for the system or lower-level components

  – Read-only sensor and other telemetry values

  – FDIR results and diagnostics

- **`ST[21]`: Request sequencing**

  Allows operators to load series of TCs to be executed in a sequential order.

- **`ST[22]`: Position-based scheduling**

  Provides the capability of executing TCs when the spacecraft reaches a specific point in its orbit.

- **`ST[23]`: File management**

  Provides the capability of managing on-board file systems, with functions such as *copy*, *move*, *delete*, or *create directory*.

## 3.2 *The SAVOIR standard*

## 3.3 *Failure causes and recovery actions*

### 3.3.1 *Failure causes*

### 3.3.2 *Preventive actions*

### 3.3.3 *Corrective actions*

# 4
# *Practical demonstration of FDIR*

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[4] M. Surligas, "SatNOGS-COMMS," presented at the CubeSat Developers Workshop, Apr. 12, 2021, p. 22.

[5] M. Langer and J. Bouwmeester, "Reliability of CubeSats – Statistical Data, Developers' Beliefs and the Way Forward," *Proceedings of the 30th Annual AIAA/USU Conference on Small Satellites*, 2016. [Online]. Available: https://repository.tudelft.nl/islandora/object/uuid%3A4c6668ff-c994-467f-a6de-6518f209962e (visited on 05/20/2021).

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