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AN AUTONOMOUS CONTROL SOFTWARE EMBEDDED IN A CUSTOM-DESIGNED ELECTRONIC ARCHITECTURE FOR EXOMARS' RLS INSTRUMENT TO ANALYZE SAMPLES AT MARS SURFACE

Laura Seoane[(1)], Sergio Ibarmia[(1)], Jesús Zafra[(1)], César Quintana[(1)], Carlos Pérez-Canora[(1)], Andoni Moral[(1)], Fernando Rull[(2)], Olga Prieto-Ballesteros[(3)]

[(1)]National Institute for Aerospace Technology (INTA), 28850 Madrid, Spain
[(2)]University of Valladolid, 47002 Valladolid, Spain
[(3)] Centro de Astrobiología (CSIC-INTA), 28850 Madrid, Spain

ABSTRACT

The software design of the RLS instrument faces the challenge of ensuring functionality and quality of science samples analyses at Mars surface, with the constraints imposed by the available hardware - such as amount of memory and computational resources -. Furthermore, as RLS is on board the ExoMars´ Rover, the instrument operations requires a high degree of autonomy that must be implemented and supported by the RLS software.

This papers shows some of the most important concepts of the RLS software design and implemented functionality. The final software product was successfully tested and integrated in all the RLS models, including the Flight Model.

1. INTRODUCTION

ExoMars mission is ESA's greatest commitment to reach the Red Planet in 2023. ExoMars will take off in September 2022 and the lander will reach Mars in June 2023. It aims to search for past/present life traces on Mars and to investigate the geochemical and environmental evolution of Mars. To fulfil these objectives, the Rosalind Franklin rover will be equipped with a large quantity of instruments that will allow to select and collect samples up to 2 meters in depth through a drill. Once samples are collected, the rover Sample Preparation and Distribution System will crush the samples and deliver the powdered material to the Analytical Laboratory Drawer (ALD). MicroOmega, MOMA and Raman Laser Spectrometer (RLS) are the three key scientific instruments included in ALD that will perform a combined analysis to extract information about composition of Mars subsurface.

RLS [1] is a Raman spectrometer which provides a powerful tool for identification and characterization of minerals and biomarkers. The instrument is made up from several units: a laser for samples excitation, an internal optical head (iOH) which collects the Raman signal returned by the sample and forwards it to the Spectrometer Unit where it is diffracted and projected to a CCD. All the mentioned operations are managed by the ICEU ("Instrument-Control & Excitation-Unit"), a custom electronic box which controls the overall instrument operation, processes spectra and provides data and power interface with the Rover. The ICEU contains the Front-End Electronics (FEE), the power board (called DCDC) and the Data Processor Board (DPU). The ICEU box also allocates the laser.

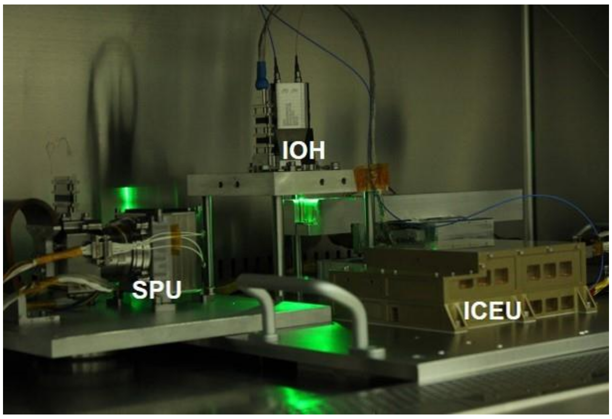

Figure 1. RLS Flight Model

2. HW CONTEXT

The RLS SW executes on a Leon2 microprocessor, located on the ICEU´s DPU. Other main elements of this board are a 32 kB PROM, a 512 kB EEPROM, a 512 kB SRAM and a 2 MB SRAM, and a FPGA supporting the CCD video data interface, implementing the CAN IP core interface and the PID controllers, and acquiring housekeeping periodically.

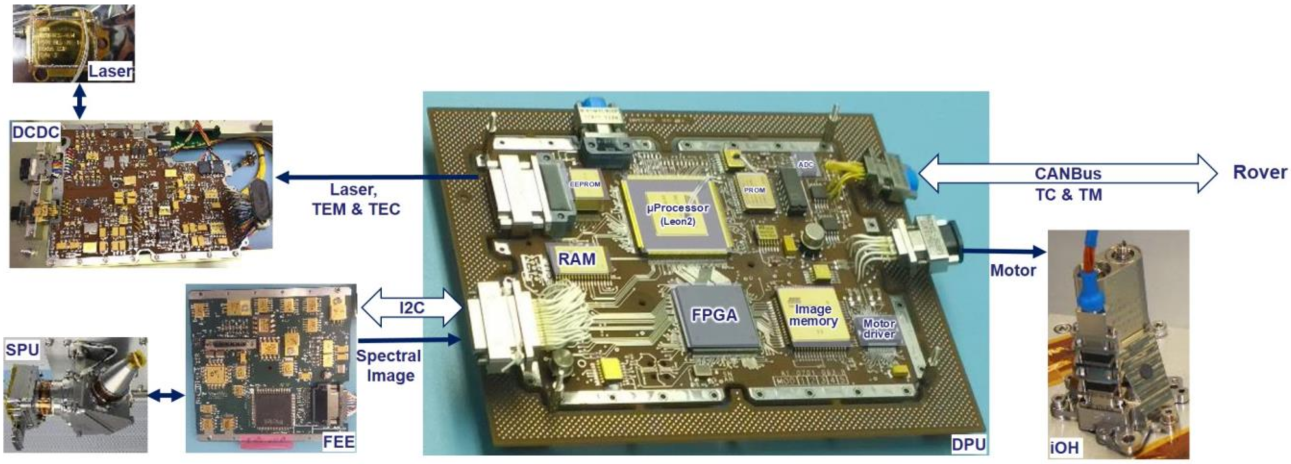

Figure 2. HW context blocks diagram

In addition, to use and manage these elements, the RLS SW must control and command other units located outside the DPU, such as the optical head focusing +mechanism, the CCD imager, and the thermal control for both, CCD and laser source, and also the communication with the Rover.

3. SW DESIGN

3.1. General considerations

The RLS SW is composed of two SW entities: the Application SW (ASW), the main element, providing control over the full operation; and the Boot SW (BSW), just performing initialization and allowing ASW updates.

The BSW is stored in the PROM and the ASW in EEPROM. In the case of the ASW, there are two images stored. So, when the instrument is switched on, the BSW checks the first image of the ASW, and if its checksum is ok, then loads this image from EEPROM to RAM. In case the check fails, it checks the second one and, if it is ok, loads this copy.

All the TCs except the rover time distribution are acknowledged when they are received through acceptance telemetry. Change mode, operation, control, test and memory related TMs are sent when the telecommanded action is finished. Event telemetry is sent just in the moment some event happens.

RLS manages onboard time internally. This time is not synchronized with Rover time. Just a correlation is done each time the rover time arrives between rover time and current onboard time. This two time values are sent together via time synchronous telemetry in order to be correlated at ground level, if required.

3.2. Operating modes

The SW design is based on a 5-modes state machine. At each state or mode a certain set of operations or activities are allowed. The RLS mode transitions can be either commanded by a specific telecommand (TC) or performed automatically. To execute any operation, RLS shall previously transit to a state where it is allowed.

The first mode is called ‘Initalization’ and it is implemented by the BSW. The ASW is in charge of the implementation of the other four modes: ‘Stand-By’, ‘Ready’, ‘Operation’ and ‘Safe’.

‘Stand-By’ is the mode where the instrument can be turned off in a controlled way. At this mode, the thermal control is not activated. Only a few TCs are accepted, most of them related to functional tests, changes in configuration parameters and transition to other mode.

The instrument will come on ‘Ready’ mode when the instrument is prepared to start the scientific operations, that is, after achieving the operative temperature. While on this mode, the instrument may run functionality tests, or launch the scientific operation.

The ‘Operation’ mode is reached in an automatic way, just after the beginning of the scientific operations. The instrument remains in this mode while is performing any operation.

The RLS ASW goes to ‘Safe’ mode automatically when any unexpected behavior is detected, although it can be also reached by TC. At this mode all the internal instrument units are moved to secure and safety conditions, and the thermal control is turned off in a controlled way.

The RLS operating modes and transitions are shown in Figure 3.

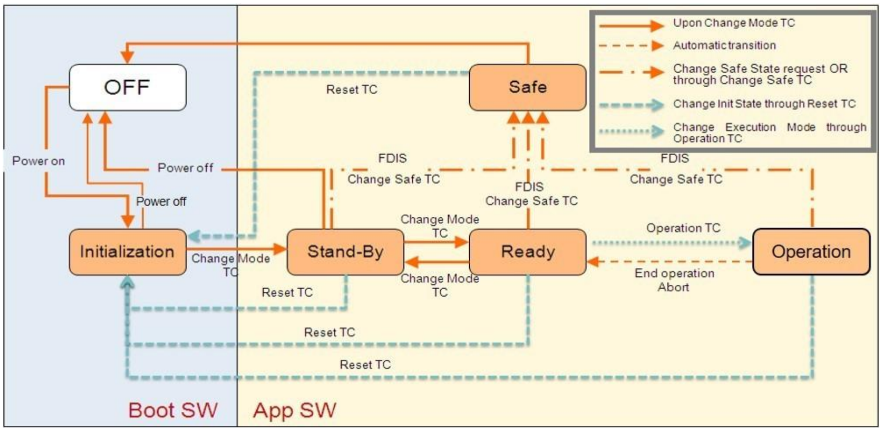

Figure 3. RLS operating modes

3.3. Main modules

The RLS ASW is composed of three main modules: ‘Application’, ‘DHS’ and ‘Environment’.

The ‘Environment’ module comprises all the low level functionalities and drivers for HW control. It manages low level interfaces, such as microprocessor and FPGA registers, timers, interrupts, on-board time, thermal control activation/deactivation, ADC interface for HK acquisition, memory banks, etc.). This module is also in charge of handling other interfaces as CAN/CANopen CCIPC IP Core [2], power on/off of different elements by commanding the DCDC board, IOH actuator, I2C communications with the FEE, CCD TEC and laser TEM control and debug serial port management.

The ‘DHS’ module covers two of the main functionalities at system level: FDIS (‘Failure, Detection, Isolation and Safety’) and communications with the Rover (TC/TM management) to transmit frames containing science, housekeeping and report information as TM data blocks, as well as receive commands as TC data blocks.

The ‘Application’ module contains the full operation functionality, the algorithms and the state machine that drives the operation modes of the instrument. Each predefined action provides a sequence of low level tasks to be performed. Keeping control while executing other background tasks and interfacing with RLS subunits, are the goals of this function. Furthermore, application module will implement scientific algorithms and CCD readout table dynamic generation.

4. SW KEY FUNCTIONALITIES

4.1. Communications with the Rover

The only interface for data transmission between RLS and the Rover OBC (On-Board Computer) is a redundant 1Mbps CAN/CANopen bus. Telecommands (TCs) and Telemetries (TMs), even long science telemetries up to around 2Mbytes, are transmitted through this bus.

To implement the interface, RLS makes use of the CCIPC CANopen IP Core developed by Sitael [3]. It is embedded in a reprogrammable FPGA where specific registers are implemented to allow the SW handle configuration and bus transfers. These registers are mapped in the I/O memory area of the microprocessor.
This IP Core was distributed by ESA to all the nodes taking part of the CAN Payload Bus.

RLS makes an extensive use of the CANopen capabilities, using synchronous PDOs (Process Data Objects) for housekeeping TMs, asynchronous PDOs for short TCs and TMs, and SDOs for long TMs and patching TCs.
All the TCs are confirmed as soon as they are received by the instrument by a PDO TM. And once the command is executed, a command-specific PDO TM is sent indicating the TC execution is finished and the instrument is ready to receive a new TC.

4.2. Thermal Control

The RLS instrument requires active thermal control for two of its main elements: the laser and the CCD image sensor.

To obtain a stabilised laser signal with the required power, it is necessary to operate the laser at a very specific and stable temperature. So, a Thermo-Electrical Module (TEM) was included to heat and/or cool the Laser unit, until it reaches its best working temperature. For this purpose, a fine control is implemented based on a PID, achieving a 0.2 degree accuracy.

On the other hand, to improve the SNR of the Raman spectra, it is needed to cool down the CCD. For this purpose, a Thermo-Electrical Cooler (TEC) was included, also based on a PID, but implementing a coarse control that allows the CCD to be cooled down to -40ºC.

These thermal control devices – the laser TEM and the CCD TEC - operate according to Peltier effect. The effect creates a temperature difference by transferring heat between two electrical junctions. A voltage is applied across joined conductors to create an electric current. When the current flows through the junctions of the two conductors, heat is removed at one junction and cooling occurs. In RLS particular case, TEM will control laser temperature by warm/cool until optimal operation temperature is reached. In the case of the RLS flight model, this optimal temperature is 29.6 ºC for the laser nominal channel and 23.9ºC for the redundant channel. Regarding the, the thermal is performed by cooling down the CCD operating temperature.

The RLS SW must ensure the right behavior of all components of the instrument in order to guarantee their safety. The Thermal Control is one of the most critical functionalities due to the high temperature gradient changes that might affect the integrity of the laser and the CCD. Therefore, activation and deactivation processes are implemented in a controlled gradual way, increasing or decreasing the current of the thermo-electrical device step by step until reaching the final objective.

4.3. LASER Driver

The Laser unit is the instrument excitation source, a diode-pumped solid-state laser emitting at 532nm. Due to the importance and criticality of this element, it has redundancy; so, the Laser unit is composed by two laser channels. Each one has its own optimum working point, what implies different signal characteristics: power, stabilization time, etc.

The RLS SW is in charge of laser channel selection, laser activation and deactivation, laser stabilization and housekeeping motorization.

Figure 4. RLS Laser unit

4.4. IOH Control

The Internal Optical Head includes a mechanism to perform an active focusing of the Laser excitation signal onto the powdered sample.

The focusing mechanism can move the focusing optics along a ±1 mm travel range using a linear ball bearing guide, while a linear encoder allows the determination of the optical position. The RLS SW commands the motor and reads the encoder to reach the desired position.

Three operation modes for the motor are available: full step, quarter step and microstepping. And two different operations are implemented by the ASW: go to a specific position on-demand and perform an Autofocus as a closed-loop algorithm, which moves the focusing optics along a 2 mm travel range until a maximum intensity of the laser reflection is achieved.

A typical Autofocus curve is shown in Figure 5.

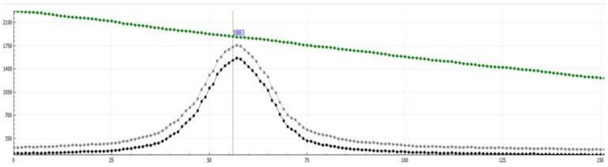

Figure 5. Autofocus graphic representation

4.5. FEE & CCD Control

The RLS SW performs the image acquisition process, including low level command generation of waves and readout tables to be executed by the FEE. It also controls when the acquired image is fully stored in the 2MB DPU's RAM, and can start to process or send it.
RLS image and spectrum

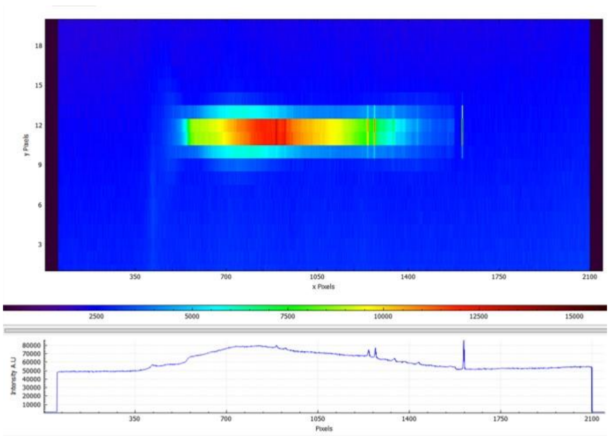

Figure 6. RLS image and spectrum example

The FEE configuration capabilities, allows the RLS SW low level control of the CCD for integration and characterization purposes such as 'Region Of Interest' determination (i.e. in which pixels the image is located), CCD noise, gain control, bias characterization, frame size, selection of using 14-bit or 16-bit by pixel, etc.

4.6. On-board processing algorithms

The RLS SW implements processing algorithms to automate the acquisition of Raman spectral data and to optimise the scientific performance.

Raman spectroscopy is a technique based on acquiring scattered photons related to molecular vibrations of the analysed materials, which happens with very low probabilities. During the ExoMars mission, the minerals and rocks that are expected to be found in Mars will be in the order from 10^{-7} and 10^{-11}. In order to be able to work with a photon flux varying in 4 or 5 orders of magnitude, it would be necessary that the CCD had a dynamic range to keep up to that range, but the technology does not provide that capacity. Thus, a set of algorithms [4][5] are implemented in the RLS SW to obtain the best configuration to perform the image acquisition.

So, when a sample is presented to RLS, first, the parameters estimation process is performed to obtain the optimum acquisition parameters for such sample and afterwards, a series of Raman images are acquired using these optimized values.

The onboard algorithms execution flow is depicted in Figure 7.

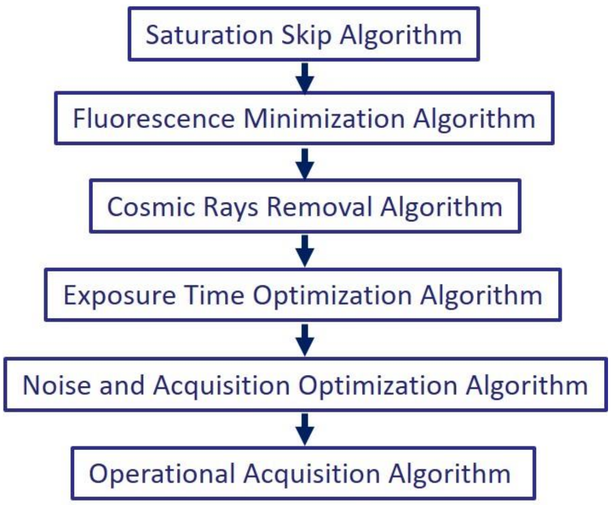

Figure 7. On-board algorithms execution flow

The function of each algorithm is the following:

- The Saturation Skip algorithm performs a continuous acquisition, gradually decreasing the CCD integration time until no pixel saturates in the spectral region of interest. It outputs an Acquisition Reference Time.

- The Fluorescence Minimization algorithm performs continual Raman acquisitions, with the previously calculated Acquisition Reference time, until the sample fluorescence signal is minimum or, at least, stable.

- Once the Raman fluorescence is minimum, the SW will ensure that the Raman acquired images are free of false signals caused by the impact of Cosmic Rays (GCRs). The Cosmic Ray Removal algorithm can be activated for this purpose, which consists of the acquisition two consecutive images, the identification of potential Cosmic Rays and their full removal. The output of this algorithm is a GCR-free image.

- Taking as input a GCR-free Raman image, the Exposure Time Optimization algorithm adjusts the exposure acquisition time to the dynamic range of the imaging CCD in order to maximize the Raman signal.

- The Noise and Acquisition Optimization algorithm estimates the SNR and calculates the optimum number of image Acquisition to minimize noise and improve Raman signal.

- And, finally, the Operational Acquisition algorithm adapts all the calculated Optimum Acquisition Parameters to the available operational resources (time, memory storage and down-link data).

5. CONCLUSIONS

In order to obtain the maximum scientific performance at the Mars surface, while optimizing the limited operation opportunities for RLS and solving the engineering difficulties intrinsic to space instrumentation, the RLS team has developed an advanced software solution that provides a full control of all RLS units as well as advanced post-processing capabilities to perform prompt in-situ analysis of Raman spectra.

Developed for a custom electronics system, with challenging constraints in terms of execution memory, data storage or power consumption, the RLS control software is capable of safely commanding and controlling all RLS critical elements, such as the optical head focusing mechanism, the CCD imager, both excitation laser sources (redundant), or their corresponding thermal control subsystems, under the severe conditions of the Martian environment. In addition, it also includes the logic to perform automated Raman acquisitions and apply a series of post-processing algorithms [4][5] to adapt the acquisition to the sample spot under analysis, by avoiding signal saturation, minimizing fluorescence background, removing undesired spikes due to Cosmic Ray impacts and by calculating the optimum acquisition times to maximize the quality of spectra.

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