Health-AI

AIKO

INFINITE WAYS TO AUTONOMY

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ADCSS – 15/11/2023

Project objective

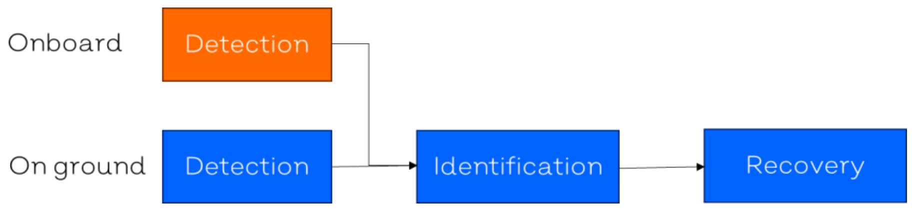
Improve the health monitoring of **satellites subsystems** by applying artificial intelligence techniques for anomaly detection and identification

→ **Development of an On-Board Health Monitoring System**

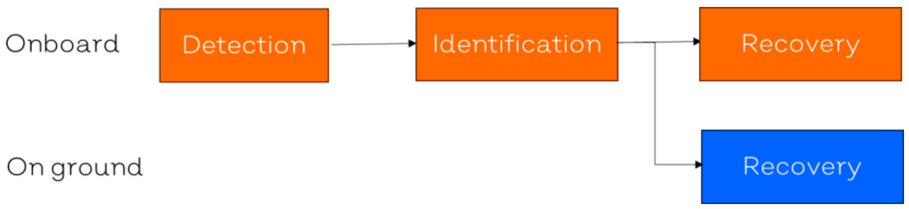
+ Funded by ESA's **ARTES programme**
+ 18 months duration
+ Target TRL 4

Project objective

TRADITIONAL FDIR



HEALTH-AI OBHMS (target)



Enabled by AI

Companies

AIKO
INFINITE WAYS TO AUTONOMY

Project lead
OBHMS design and development

INGENIArs

Hardware architecture
DL model porting and optimization

tyvak International SRL

Use cases and dataset
Benchmarking

TECHNOLOGY
TRUSTED BY SEVERAL SPACE CUSTOMERS

ON-BOARD
A SMART BRAIN FOR AUTONOMOUS SATELLITES

GROUND
CONTINUOUS INTELLIGENCE FOR OPERATORS

AIKO

INFINITE WAYS TO AUTONOMY

We help you forget that space operations are complex.

OBHMS DESIGN

SW design

+ Built on AIKO's **orbital_OLIVER** product for onboard autonomy

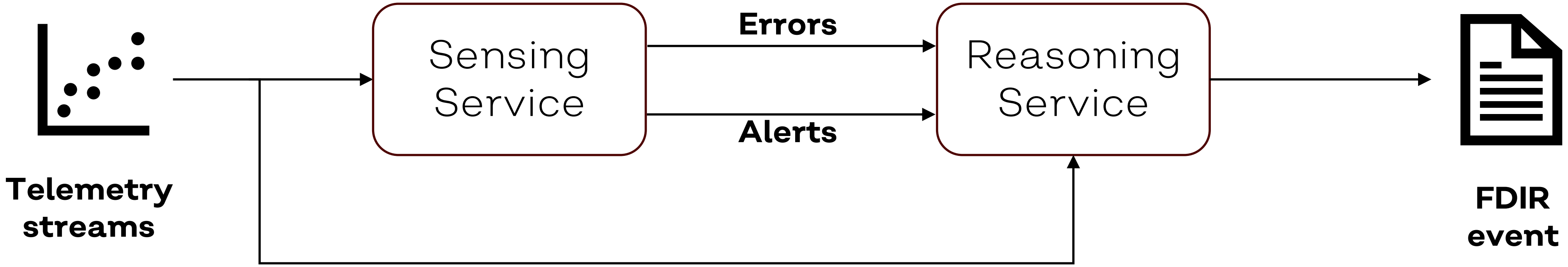
+ Manages **spacecraft resources**
  (Power, bandwidth, telemetry, payload data)

+ **Highly configurable modular** framework

SW design

Two-step approach:

+ **Sensing Service** → Semi-supervised DL models → **Anomaly detection**
+ **Reasoning Service** → Knowledge-based system → **Classification**



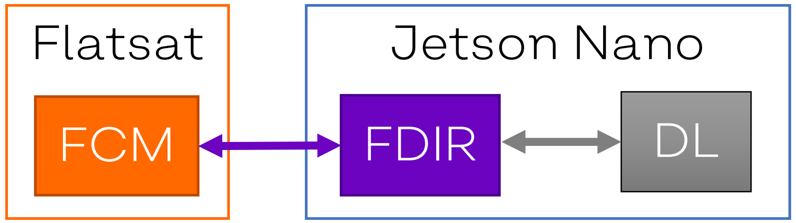
SW design

- **Semi-supervised DL models:**
  - Rely only on abundant nominal data
    (whereas small and incomplete anomalous dataset usually available)
  - Independence from the set of known anomalies
    (remains valid if the set is extended with new anomaly classes)

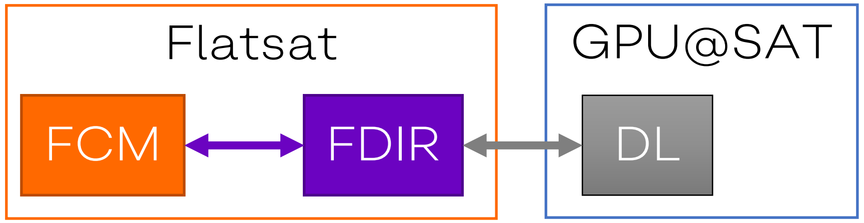
- **Knowledge-based system:**
  - Exploit domain knowledge to augment information from small anomalous dataset
    (not data hungry)
  - Fully explainable
    (in contrast to black-box DL, especially valuable for the classification step)

HW design

Try dual configurations to explore pros and cons



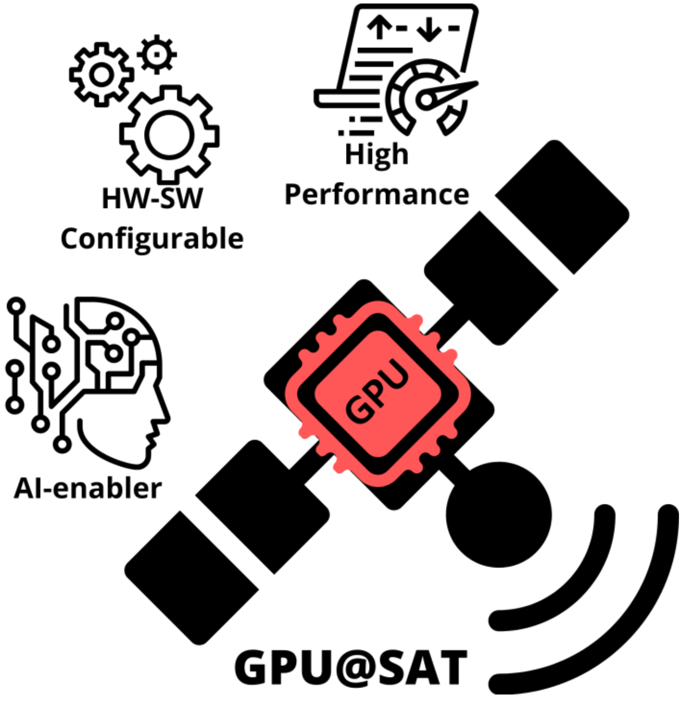
- The whole OBHMS run on a dedicated board
- Higher computational power
- No radiation tolerant



- Only the DL models run on a dedicated board
- Lower computational power
- High radiation tolerance

GPU@SAT: what is it?

+ IngeniArs' **GPU Soft Core** for FPGA/ASIC
+ Specific for on-board data processing and data handling
+ Enables a fully **Space-Qualified and flexible** solution for Artificial Intelligence, Computer Vision and High-Performance Computing.



GPU@SAT: features

+ **Integrated in any FPGA available onboard** (Space qualified or Commercial)
  + Standard AXI bus interface
  + External interfaces inherited from the board
+ **Highly Scalable and Flexible**
  + Customizable number of Computational Unit Cores and CU-shared memory size
  + Integration of custom processing blocks in (e.g., image pre-processing)
+ **Task scheduler** to execute multiple neural networks at time
+ **Power Consumption**
  + < 5 W increase on FPGA power consumption due to GPU@SAT
  + Scale with the number of CU Cores
+ **Dedicated Framework** to compile and port applications directly on the IP core
  + Library of applications available (e.g., Post training quantization service)

GPU@SAT: Health-AI advancements

+ **LSTM layers now supported by GPU@SAT ecosystem**
    + Also with autonomous quantization and scheduling tools

+ **Dedicated kernel module for Petalinux for scheduling and managing Xilinx board**
    + New memory management system implemented to handle the high number of weights of LSTM layers
    + Autonomous kernel switching in GPU@SAT via OS

PROJECT RESULTS

Use cases

+ From Tyvak's real mission experience
+ 6-12U CubeSats in LEO
+ Covering diverse subsystems

ADCS anomaly detection

RW, IMU, SAS

Long-period memory trend

EPS bus voltage prediction

Test campaign

+ All 3 use cases:
  ADCS, SW, EPS
+ 3 different satellite platforms
+ 2 HW configurations:
  Jetson Nano, GPU@SAT
+ 2 datasets:
  real, synthetic

ADCS: dataset

+ Small dataset of real mission anomalies (from 3 platforms)
+ Larger dataset of high-fidelity synthetic examples

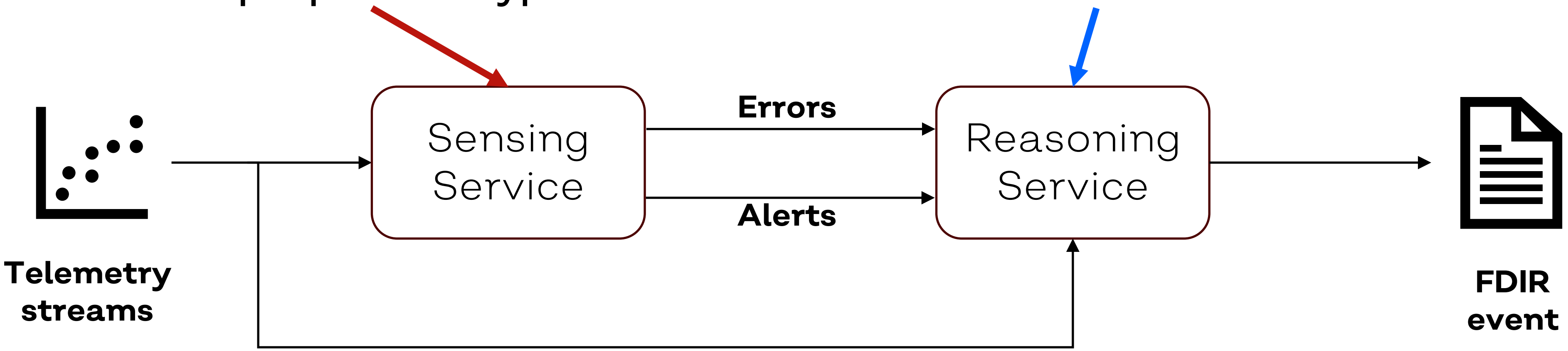
RW anomalies	41 (10)	IMU anomalies	22 (2)	SAS anomalies	20 (10)
Controller instability	13 (3)	Stuck IMU	11 (1)	Non-silent stuck SAS	10 (0)
Wheel stiction	4 (4)	Out-of-scale IMU	11 (1)	Silent stuck SAS	10 (10)
Desaturation fault	11 (0)				
Nominal detumbling*	10 (0)				
Nominal strain*	3 (3)				

*Nominal behaviours that should not be flagged as anomalous.

ADCS: implementation

+ 3 LSTM-based models
  + RW speed
  + IMU body rates
  + SAS sun intensity
  + **1 set per platform type**

+ Additional TM analysed:
  + RW voltages and currents
  + Magnetorqers torques, voltages and currents
  + ADCS operational state



ADCS: model porting

	Jetson Nano	GPU@SAT
Quantization	16 FP (inner layers only)	Int11 (stored in 32)
Accuracy drop	1-6 $*10^{-6}$	1-5 $*10^{-3}$
Inference time	0,04-0,05 s	14-15 s
Model size	5.6 MB	1.4 MB
Avg power	3.7 W	< 4.1 W

Xilinx ZC706 SoC
(Cortex-A9 CPU + Xilinx XC7Z045)

ADCS: detection results

+ Detection of true anomalies

	Synthetic				Real				
CASE	Total	H-AI	FDIR	Avg delay Jetson	Total	H-AI	FDIR	Avg delay Jetson	Avg delay GPU@SAT
Controller instability	10	10	0	warning	3	3	0	warning	warning
Wheel stiction	-	-	-	-	4	4	4	-00:00:30	-00:00:15
Desaturation fault	11	11	11	-00:36:44	-	-	-	-	-
Nominal detumbling	10	10	0	ground	-	-	-	-	-
Stuck IMU axis	10	10	10	00:06:36	1	1	1	00:07:00	00:08:00
Out-of-scale IMU	10	10	8	-00:06:22	1	1	1	-00:01:00	00:00:00
Stuck SAS	10	3	0	ground	-	-	-	-	-
Slient stuck SAS	-	-	-	-	10	7	0	ground	ground

ADCS: classification results

+ Classification of true anomalies
+ Consistent across HW configurations

	Synthetic									Real								
CASE	Controller ins	Wheel stictio	Desaturation	Nominal detu	Stuck IMU ax	Out-of-scale	Stuck SAS	Slient stuck S	Undetected	Controller ins	Wheel stictio	Desaturation	Nominal detu	Stuck IMU ax	Out-of-scale	Stuck SAS	Slient stuck S	Undetected
Controller instability	8	0	0	0	0	2	0	0	0	3	0			0	0		0	0
Wheel stiction	-	-	-	-	-	-	-	-	-	0	4			0	0		0	0
Desaturation fault	2	0	6	0	0	3	0	0	0									
Nominal detumbling	0	0	0	10	0	0	0	0	0									
Stuck IMU axis	1	0	0	0	9	0	0	0	0	0	0			1	0		0	0
Out-of-scale IMU	5	0	1	0	0	4	0	0	0	0	0			0	1		0	0
Stuck SAS	0	0	0	0	0	0	2	0	7									
Slient stuck SAS	-	-	-	-	-	-	-	-	-	0	0			0	0		10	0

ADCS: false alarm rate

Dataset	HW	Total	w/o silent SAS
Real	Local	1 / 15.78	1 / 126.25
	Jetson	1 / 24.0	1 / 37.1
	GPU@SAT	1 / 18.5	1 / 30.0
Synthetic	Local	1 / 11.26	1 / 20.91
	Jetson	1 / 12.6	1 / 18.9

ADCS: result highlights

+ More than **88%** of the anomalies are **correctly detected**.
+ More than **65%** of detections happen **in advance** with respect to traditional FDIR routines.
+ More than **66%** of the anomalies are **correctly classified** after being detected.
+ **False positive rate is too large** for application to a real mission

Fault start: 07:09
H-AI detection: 08:35

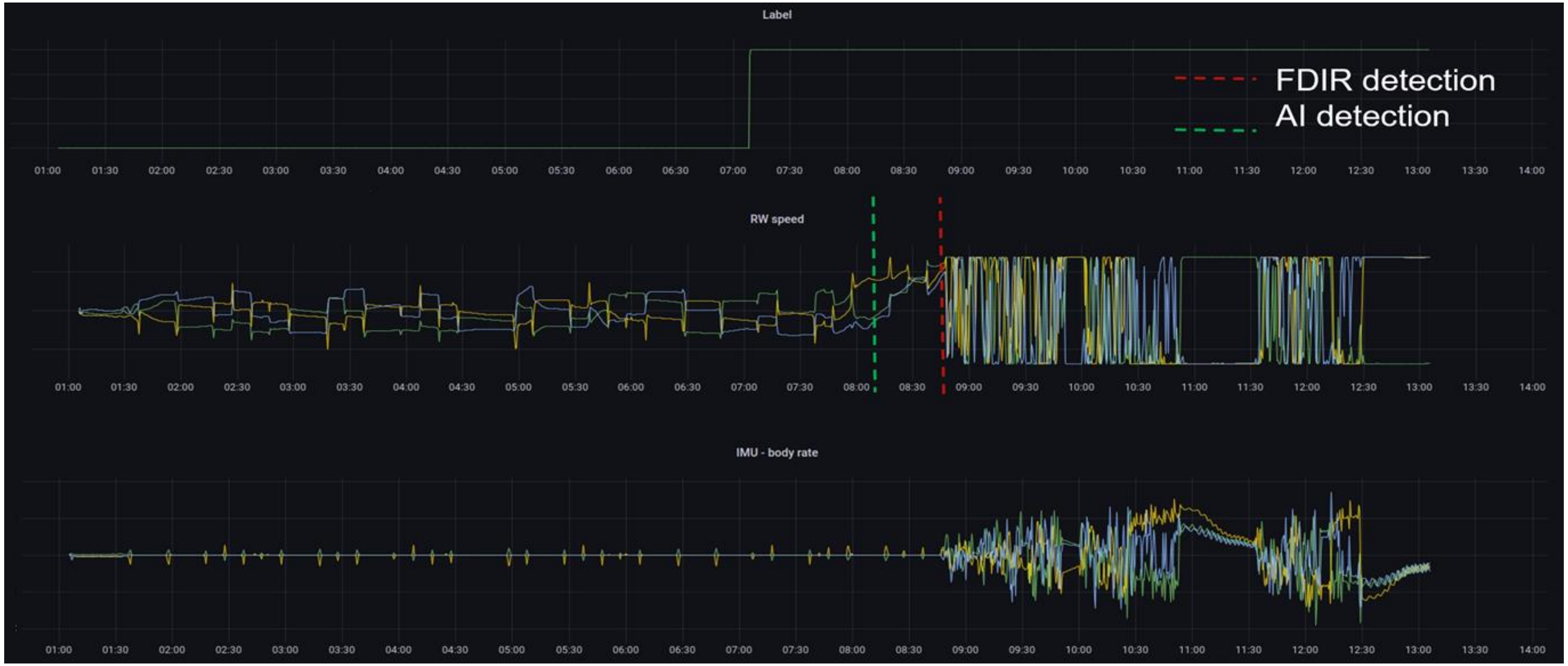
ADCS: example

RW desaturation tool fault (synthetic)

Fault start: 07:09
H-AI detection: 08:35
FDIR detection: 08:47

ADCS: example

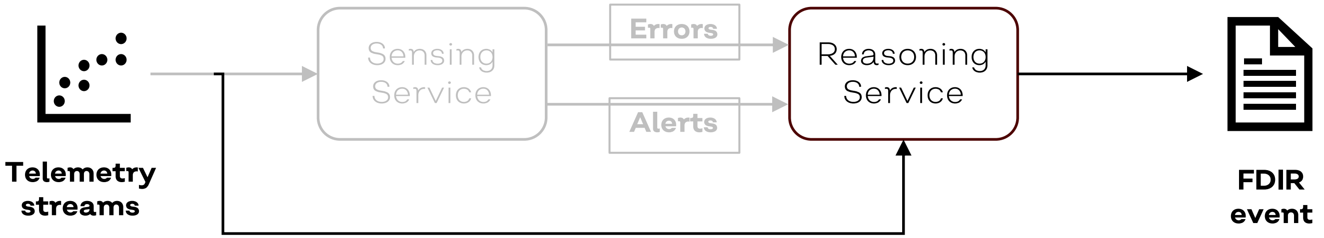
RW desaturation tool fault (synthetic)



THE OTHER USE CASES

Memory trend use case

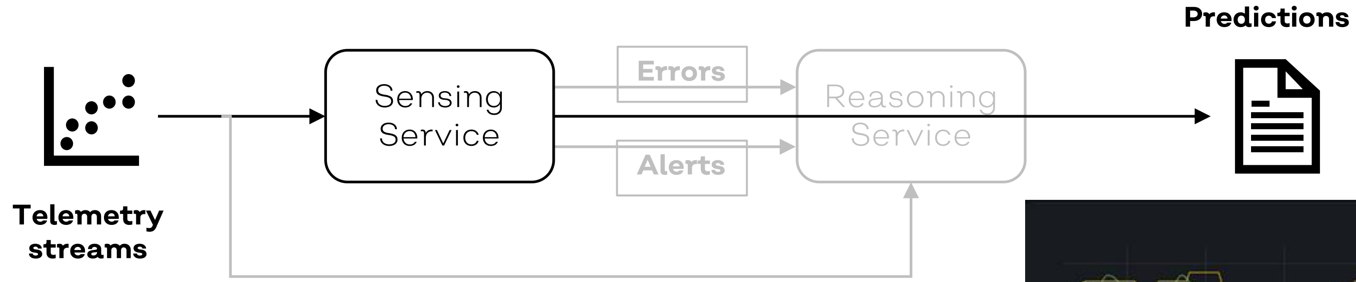
- Anomalies in file management by the OBC
- Rely only on the Reasoning Service (exploit orbital_OLIVER flexibility)
  - Sorage levels, CPU load, CPU uptime

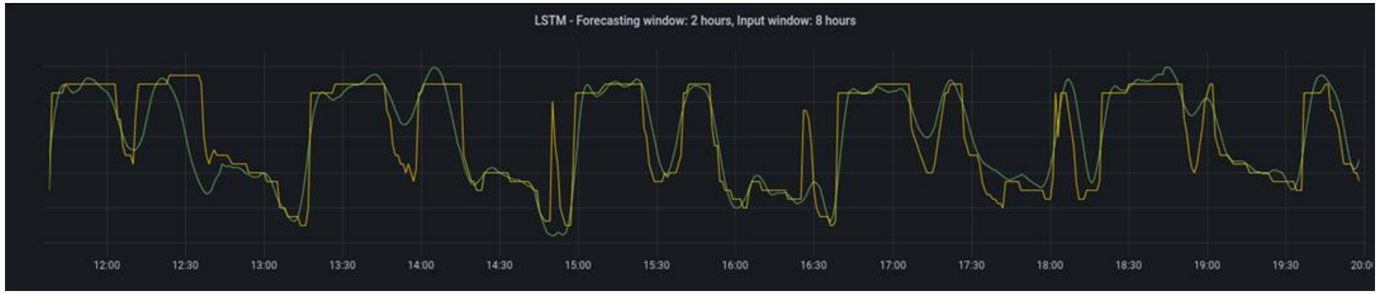


CASE	Tools fault	Data generat	Storage leak	Undetected
Tools fault	9	0	0	0
Data generation	0	8	0	1
Storage leak	8	0	0	1
Storage leak (deep cleening)	0	0	8	0

EPS: Bus voltage prediction

+ 90 min forecasting
+ Can be exploited for better payload duty cycle management
+ Rely only on the Sensing Service (exploit orbital_OLIVER flexibility)
    + 1 LSTM-based model with bus voltages and currents as inputs





EPS: Bus voltage prediction

Increasing footprint

Test metrics		
MAE	**MSE**	**RMSE**
0.035	0.003	0.053
0.033	0.003	0.052
0.032	0.003	0.057

EVALUATION AND PROSPECTS

Evaluation

+ **Generally positive results**, although some pain points and room for improvement have been identified

+ **Limited scalability** to cover the full onboard telemetry and subsystems, especially for large missions

  → focus on subsystems where the OBHMS can be most useful, e.g. for improved safety or automatic recovery

+ The best way to **interact with traditional FDIR** system must be investigated

Prospects

tyvak International SRL

- Onboard health monitoring brings **benefit** to mission operations even if no automatic recovery action is taken
  - Select telemetry to download, support operators' root cause analysis
  - Early adoption is possible even if some elements are at a lower maturity
- Interest in integrating the OBHMS as a **secondary payload**
  - Extra space and power budget often available on standard missions
- **IODs** are paramount to reach commercial maturity
  - Streamlining of the product lifecycle from mission design to operations, including reuse across different missions

Thanks for your attention!

AIKO

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