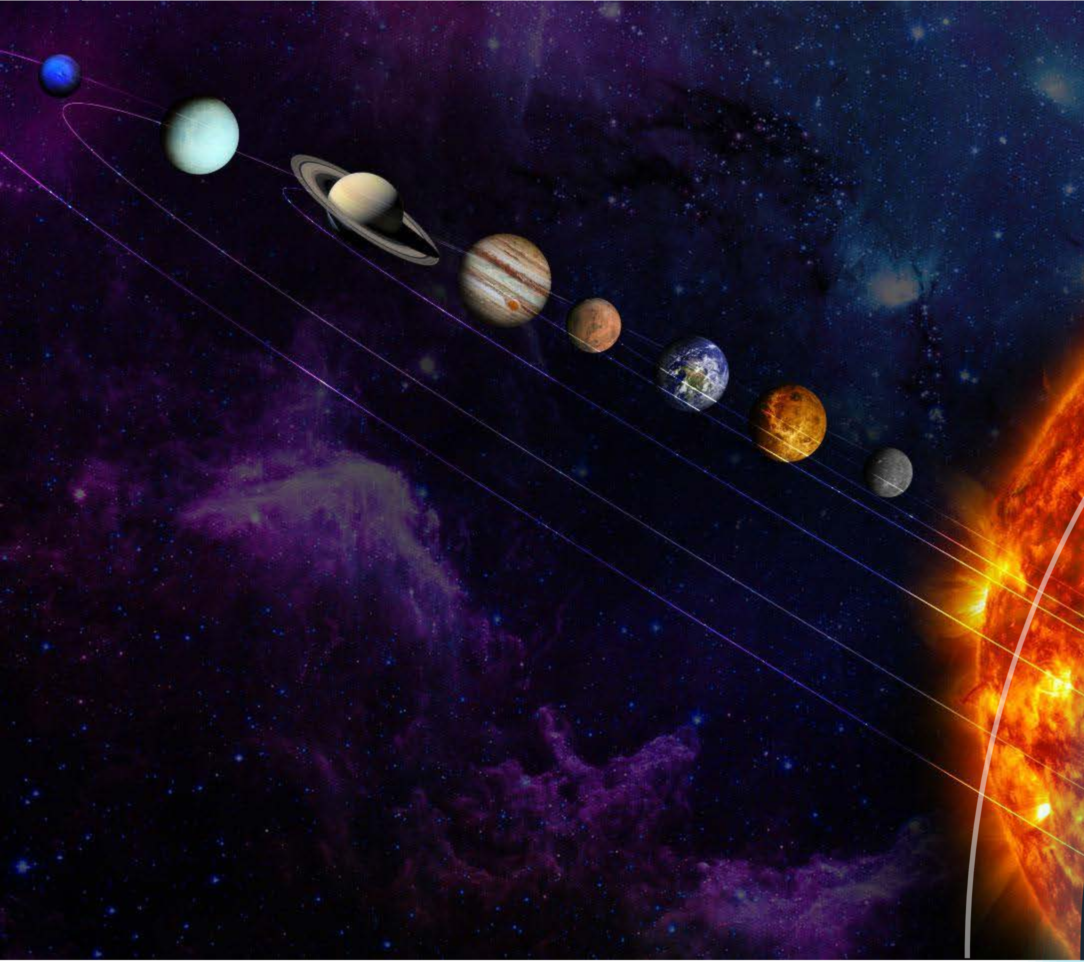

STATE-OF-THE-ART & PERSPECTIVES OF AUTONOMY AND GNC/FDIR COUPLING

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ADCSS – 14/11/2019 - ESTEC

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GENERAL CONSIDERATIONS - FDIR HIERARCHICAL ARCHITECTURE

- AOCS FDIR architecture is based on principles as described in the SAVOIR FDIR HANDBOOK

A LAYERED APPROACH OF DETECTION

SW implementation using PUS(12) SVC : PMON, FMON

- Unit monitoring based on DCC & EIC
- Functional monitoring : control, rates, speed, guidance … error

Level	Failure Description
D0	Failure detected and identified internally by a unit or function, with no impact on S/C behaviour, or failure not to be compensated for by the FDIR system (i.e. failure handled by the Ground Segment).
D1	Single failure of one unit degrading or interrupting the service provided by that unit.
D2	Failure of functional chain performance.
D3	Failure of the Central Software (CSW).
D4	Failure with major impact on satellite control triggering System Alarms or (CSW) Software Alarms.

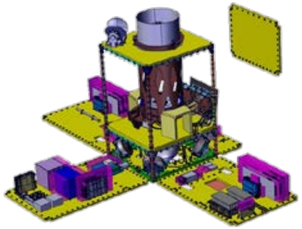
AND GRADUAL RECOVERY ACTIONS

Set of commands triggered PUS(19), (18) or (21) SVC: OBCP, TC sequence

- Unit reconfiguration controled by OBSW
- AOCS units reconfiguration controled by OBSW
- Mission/phase dependant

Level	Recovery Action	Remarks	Hierarchy
R0	Unit-level internal recovery (transparent to upper levels; not always reported)	Associated to an internal failure in one unit or function, and recovered by internal functionality	Unit
R1	Local reconfiguration (retry, then switch off or switch over)	Unit reconfiguration or re-initialization	Unit
R2	Functional chain mode change or reconfiguration	Requires changing the mode of a function, but it is possible to maintain the current satellite mode or to make a transition to another satellite mode different from the satellite safe-mode	Functional chain
R3	Computer re-initialization or recovery; possible satellite mode change	Includes, in particular, failures that need to be neutralized by the reconfiguration module; limited mission suspension	Functional chain or satellite
R4	Satellite safe mode triggering	Failures that cannot be recovered at lower levels and thus require a transition to SAT Safe Mode	Satellite

SUMMARY OF AUTONOMY IMPLEMENTATION HISTORY / LEVELS



- Autonomy has always been linked with the capability of detecting and correcting failures on-board (FDIR)
- Simple S/C design, low computing capabilities, simple FDIR :
  - FOR ANY DETECTION OF FAILURE ON-BOARD:
    - Switch off the payload
    - Go to safe mode (ensure solar power on solar panels, minimize fuel consumption)
  - RECOVERY IS SIMPLE (AND RELIABLE!) BUT HAS THE DRAWBACK TO STOP THE MISSION FOR SOME TIME (HOURS/DAYS)
  - GROUND IS COMMANDING ALMOST EVERYTHING

- More sophisticated FDIR in order to maintain the mission in case of “simple” failures :
  - FEW LEVELS (4) IN THE FDIR SUCH THAT FAILURES TYPICALLY AT EQUIPMENT LEVEL ARE MANAGED ON-BOARD (AUTONOMOUS SWITCH TO REDUNDANT UNITS): THIS IMPLEMENTED STEP IS ALREADY COSTLY IN TERMS OF DESIGN AND VALIDATION
  - INTERMEDIATE MODES OF OPERATIONS IMPLEMENTED (DEGRADED POINTING TYPICALLY) IN ORDER TO SHORTEN THE RECOVERY IN NOMINAL CONDITIONS
  - MORE AUTOMATION OF SOME SEQUENCES OF EVENTS (E.G FOR CONSTELLATIONS AT SEPARATION)

- Very sophisticated FDIR/autonomy when it is required (typ. Interplanetary missions) :
  - IMPLEMENTATION OF HOT REDUNDANCY (FAIL OPERATIONAL) FOR SOME CRITICAL PHASES
  - SEQUENCE OF EVENTS CAN BE VERY SOPHISTICATED, WITH EVENTUALLY NOT WELL KNOWN ENVIRONMENT

FDIR EXOMARS 2016 TRACE GAZ ORBITER (1/3)

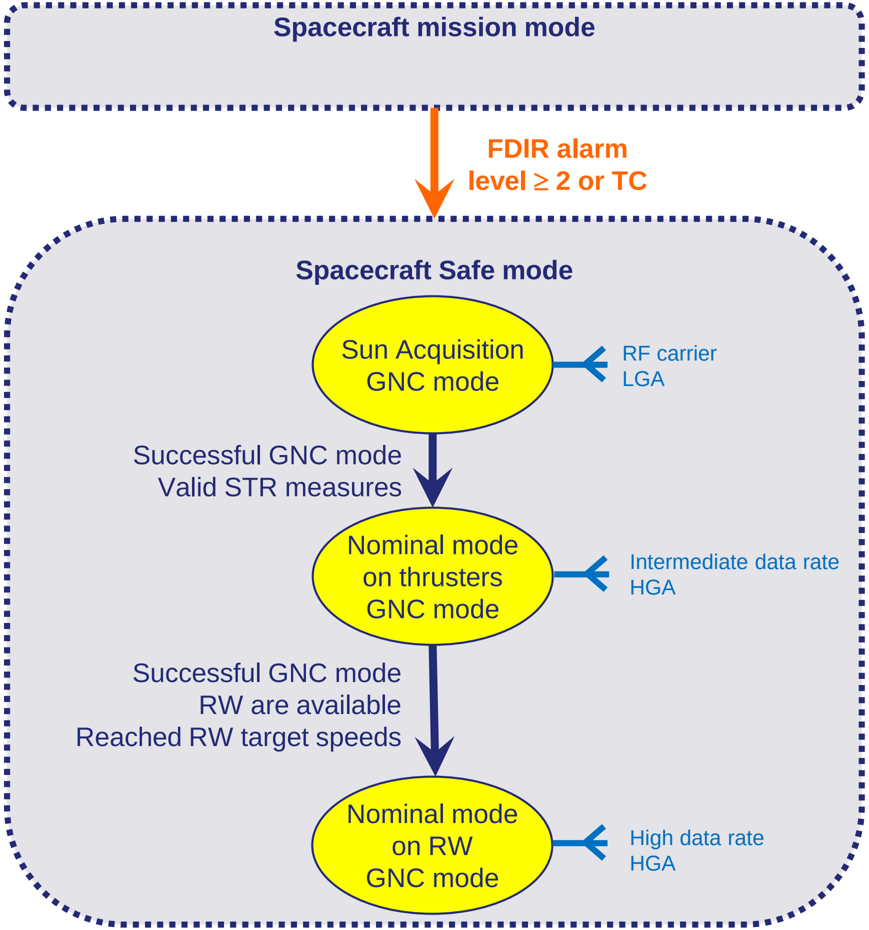
General ExoMars FDIR principles:

Failure detection level	Failed entity	Detection principle	Recovery action
0	Inside unit	Built-in detection	Unit internal correction
1	Unit failure localised without ambiguity	Detected by central SW, through acquisition of health statuses and critical parameters	Switchover to the backup unit
2	Vital spacecraft functional chain performance anomaly	Detected by CSW, through function performance monitoring	Fail-Safe: Transition to spacecraft Safe mode Fail-Op: Use of all backup units, keeping the current spacecraft mode
3	SMU failure	Watch dog	Fail-Safe: Transition to spacecraft Safe mode Fail-Op: Use of all backup units, keeping the current spacecraft mode
4	Global spacecraft malfunction	Hardwired alarm	Fail-Safe: Transition to spacecraft Safe mode Fail-Op: Not applicable (level 4 inhibited in Fail-Op phases)

FDIR EXOMARS 2016 TRACE GAZ ORBITER (2/3)

ExoMars Fail-Safe strategy:

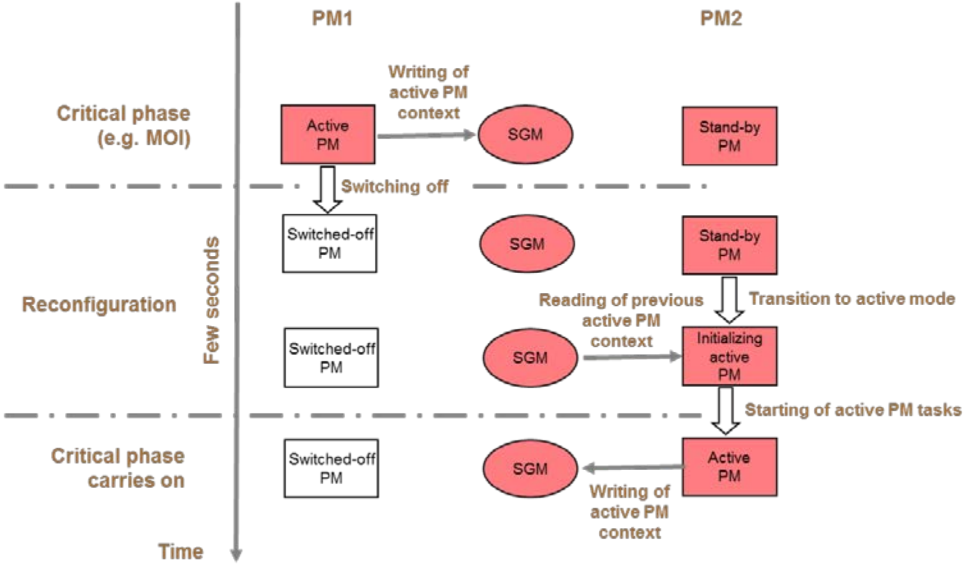
- In case of FDIR detection of level ≥ 2 or dedicated TC, the spacecraft mode transits to Safe.
- In Safe mode:
  - AOCS secures the spacecraft integrity with Sun oriented mode, sending RF carrier through Low Gain Antenna (LGA).
  - Then AOCS autonomously escalates to nominal mode on thrusters in order to allow the steerable High Gain Antenna (HGA) pointing to Earth.
  - If Reaction Wheels (RW) are available, AOCS autonomously escalates to nominal mode on RW in order to:
    - Increase accuracy of HGA pointing to Earth.
    - Save fuel.



FDIR EXOMARS 2016 TRACE GAZ ORBITER (3/3)

ExoMars Fail-Op strategy:

- In some critical mission phases, the current spacecraft mode is maintained whatever the failure level is, i.e. transition to Safe mode is forbidden.
- This is in particular the case in Mars Orbit Insertion (MOI) manoeuvre, where the engine thrust must not be interrupted for more than 10 s.
- The solution implemented on ExoMars is:
  - To power on all the backup avionics units in order to quickly take over in case of equipment failure.
  - To power on the backup Processor Module (PM), in order to save the boot and SW initialisation time.
  - If the nominal PM fails, the backup PM takes over the control of spacecraft, on the basis of context previously saved in Safe Guard Memory (SGM) by the nominal PM.



MAIN TRENDS FOR AUTONOMY IN SPACE SYSTEMS

Higher level of autonomy is required for several different reasons :

- Technology evolution (electrical propulsion): large gain of mass but orbit raising may take several months and is better managed through autonomous navigation and autonomous orbit maneuvers computed on-board
- New market (large constellations): separation sequences, orbit insertion and control maneuvers
- Clean Space/Servicing
- Increased reliability of interplanetary missions (in not well known environment): capacity of changing mission parameters in real time in order to make the mission safer or with a better accuracy thanks to shorter decision loops
- Add autonomous on-board capability to define the instrument acquisition plan and/or the TMI download plan (typically for Earth Observation satellites) such as to maximize the observation of areas of interest
- Increased autonomy on payload data quality & automated filtering (deletion of irrelevant or spoiled data)
- Predictive maintenance & advanced FDIR

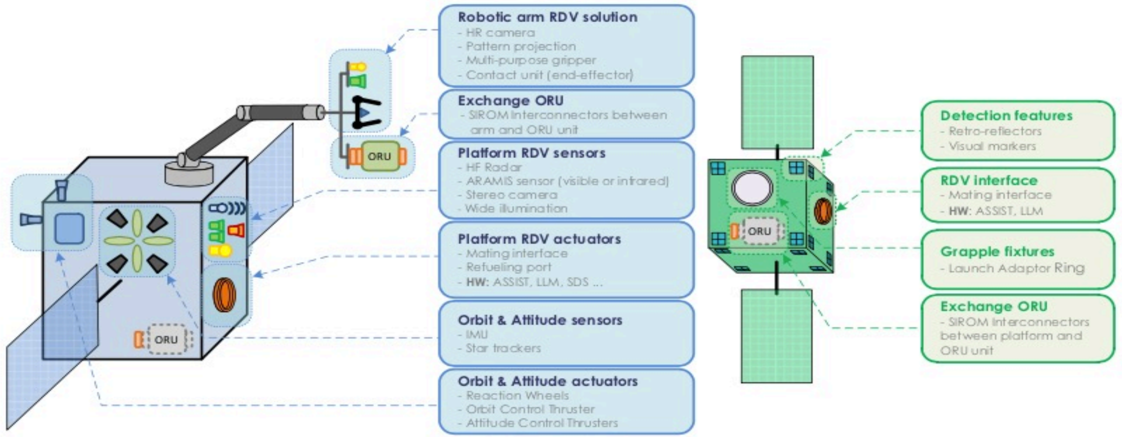
From these needs the trends can be considered as follows :

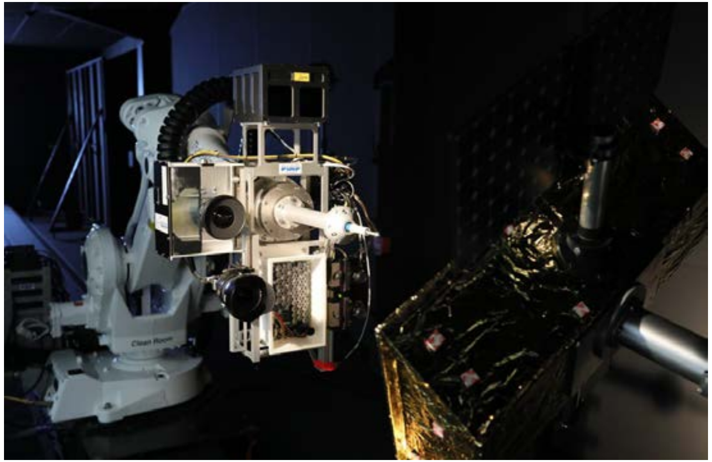
- Autonomous maneuvring capability for all S/C in Earth orbit: orbit determination, path planning, advanced GNC
- Use of some instruments data in real time to upgrade the mission time-line without Ground intervention / autonomous RDV, autonomous landing & rover operations
- Work on Satellite HKTM and internal satellite data (complementary to the SDB) for a next step of FDIR capabilities

OVERVIEW OF SHORT-TERM HIGHLY AUTONOMOUS SYSTEMS

ROBOTIC MISSIONS & ON-ORBIT SERVICING

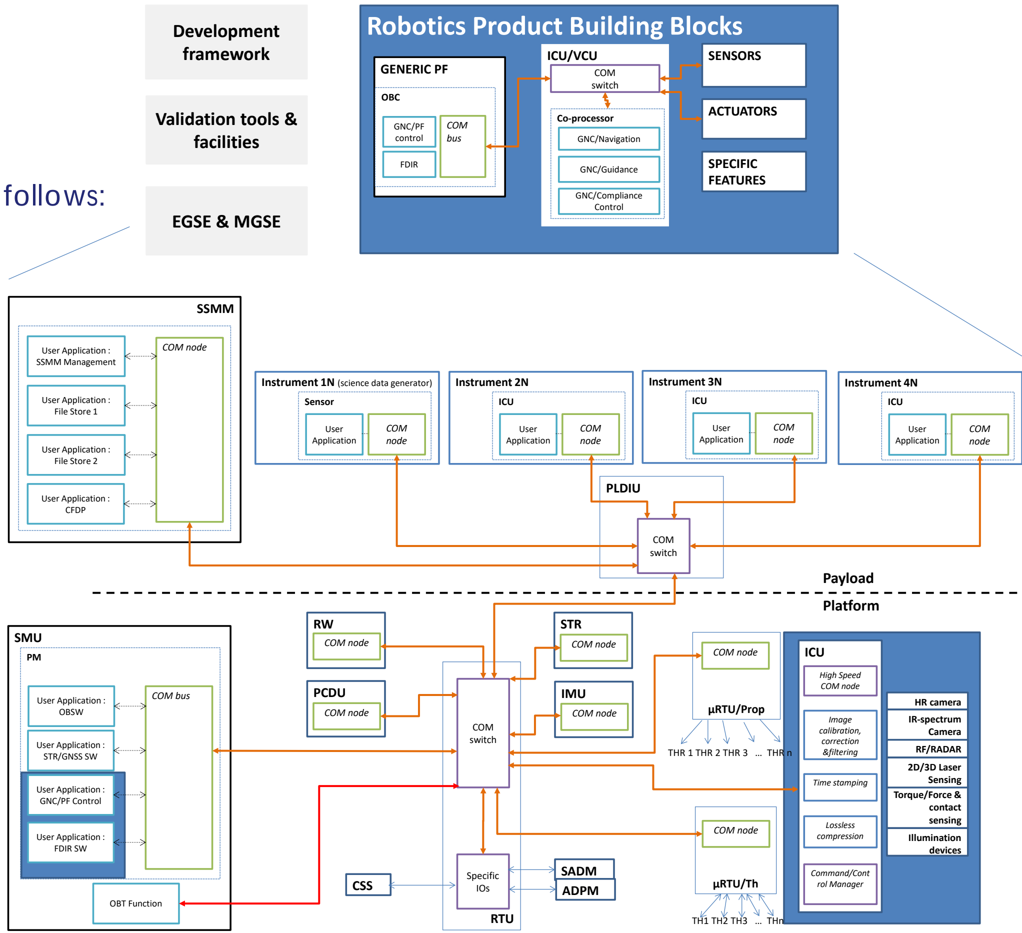
- Generic building blocks to be instanciated per mission (rendez-vous, servicing, robotic exploration & science)
  - Specifics in terms of autonomy & FDIR
    - High frequency control loops & decision making requires high autonomy (e.g.: CAM, path planning)
    - Advanced FDIR with maximisation of Fail-Op recoveries



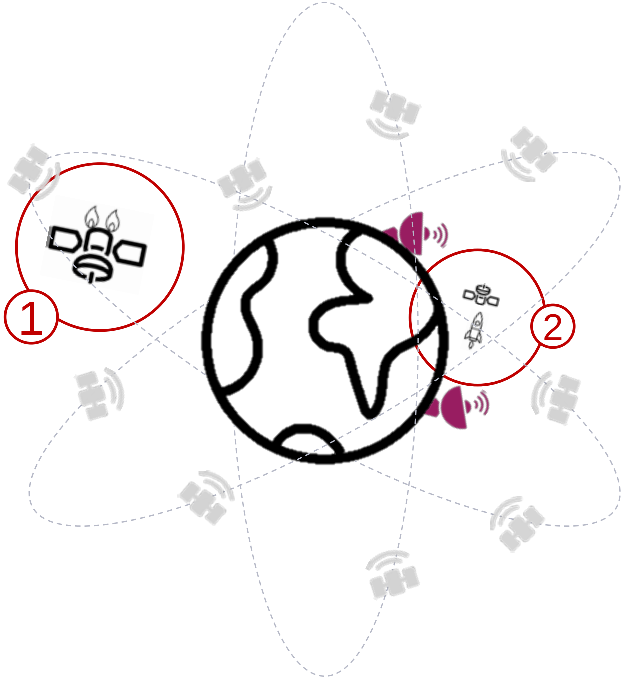


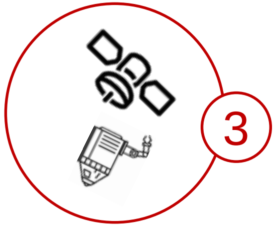
ADVANCED GNC CHAIN IN THE AVIONICS ARCHITECTURE

- The robotic chain for GNC can be broken down as follows:
  - **THE ROBOTIC COMPUTING SYSTEM**
  - **THE ROBOTIC SENSORS**
  - **THE ROBOTIC ACTUATORS**
  - **THE GNC ALGORITHMIC CHAIN**
    - Relative & Absolute Navigation
    - Guidance
      - Long-range guidance
      - Inspection
      - Vicinity maneuvers
    - Control
      - Local & composite control
      - Multi-DoF & flexible structures
  - **THE DEVELOPMENT FRAMEWORK, EGSE & TEST LABS**

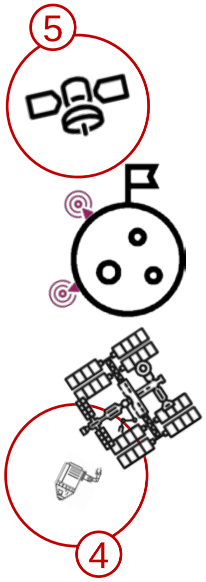


OTHER EXAMPLE OF R&D FOR AUTONOMOUS GUIDANCE: MUSE4PNT





#	Mission	Potential sensors and technologies
1	Autonomous orbit raising & station keeping	GNSS | INS
2	Post separation optimization	GNSS | INS
3	On-orbit servicing (LEO, GEO)	GNSS | INS | Radar | Lidar | Cameras | Tactile sensors
4	In-orbit servicing (lunar)	GNSS | INS | Radar | Lidar | Cameras | Tactile sensors
5	Lunar vicinities navigation	GNSS | INS | Cameras | Lunar ground support | Other spacecraft



AI IN SATELLITE AVIONICS ?

From vision-based nav to control through the Data Management System

- **ORBITAL RENDEZ-VOUS REQUIRE MULTIPLE SENSORS FOR FUNCTIONAL REDUNDANCY (VIS-NAV; IR-NAV; LIDAR)**
  - AI for image fusion at early stage in the processing chain
  - Long range (1500km to 50m): AI for bearing-only navigation (few pixels)
  - Short range (<50m): AI for pose estimation (relative attitude and position)

- **RENDEZVOUS REQUIRES OPTIMAL TRAJECTORY PLANNING FOR SAFE CLOSE-RANGE MANOEUVERS AND DV OPTIMISATION TO TARGET INTERFACE**
  - AI for long-range (kms down to 50m) trajectory planification
  - AI for close-range (<50m) trajectory optimization to target capture (DV minimization; safe approach)

- **FDIR/MONITORING:**
  - AI to identify dangers during the operation - Analysis of trends in dynamics and health monitoring
  - AI to provide higher availability of space systems

- **CONTROL OF ACTUATORS (THRUSTERS, RW, ROBOTIC ARM, GRIPPER)**

CONCLUSION

- Autonomy is increasing in most of the space systems to:
  - **FACILITATE OPERATIONS**
  - **SHORTEN THE REACTION LOOPS FOR MORE AMBITIOUS & EFFICIENT MISSIONS**
  - **ENABLE NEW MISSIONS, IMPOSSIBLE OTHERWISE**
  - **INCREASE AVAILABILITY OF SPACE SYSTEMS**

- Building blocks developed in specific highly challenging contexts *(e.g: On-Orbit Servicing)* can benefit other Product Lines!

- AI is a way forward, it is not the only one

END OF PRESENTATION

Thank you for your attention

Questions?