Avionics for Low Cost Fast-Track Planetary Missions

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Summary

- -Company Overview
- -UAV GNC Development
- -Space GNC Development
- -Technology and Market Developments Relevant to GNC
- -Accelerating GNC-Related Technology Development
- -Recent Applications to ESA Projects
- -Enabling Low-Cost Exploration

Company Overview

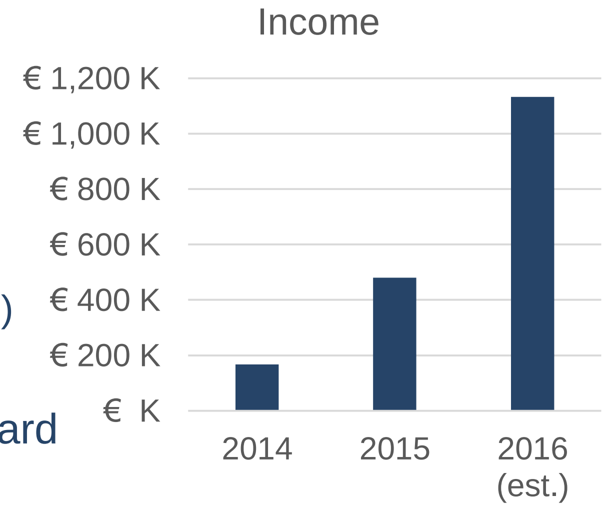
Company Profile

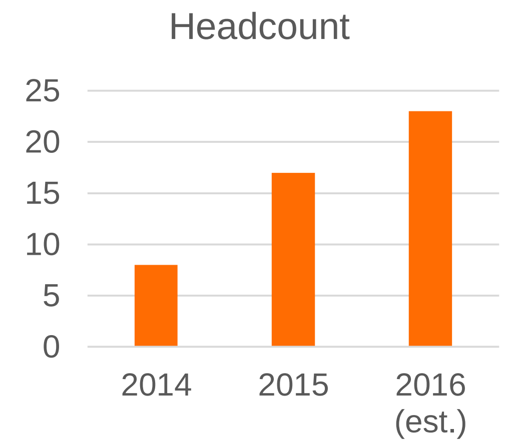
Spin.Works, S.A.

- **Founded in 2006**
  - **Partners:** broad-based professional experience at top aerospace institutions (Airbus, Astrium, ESOC, NASA, McLaren F1)
  - **Primary focus:** drone-related technology R&D (esp. atmospheric GNC)
- **Investment Strategy:**
  - **Initial focus:** micro-drone hardware+software (real-time onboard and ground segment-related) development
  - Evolution towards **value-added technologies and services** (mapping, forestry, precision agriculture)
- **Fields of expertise:**

- **Space**: Mechanisms, AOCS/GNC & Machine Vision

- **Autonomous Systems (drones)**: Imaging & Data Services

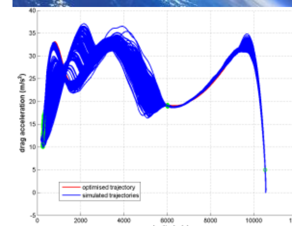


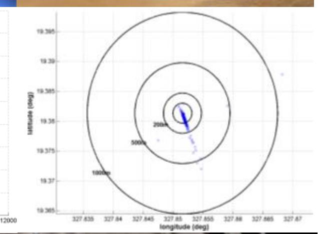


Flight Control and Avionics

- Knowledge Base

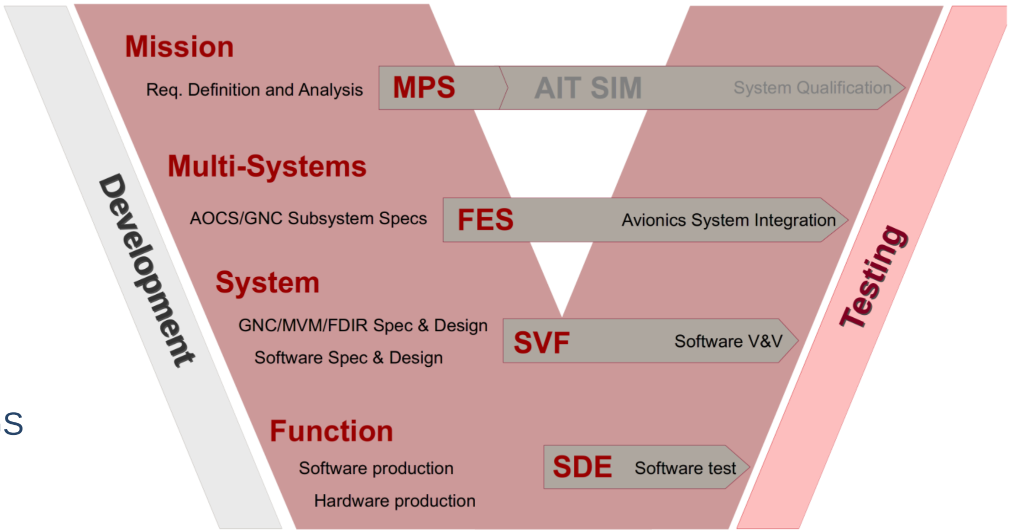
- **Entry, Descent and Landing GNC (ESA):**
  - Precision (<100m) Entry Guidance (Earth, Mars)
  - Terminal Area Energy Management (capsules, lifting bodies, space planes)
  - Powered Descent Guidance and Control
  - Vision-Based Navigation
- **Hazard Detection and Avoidance (ESA):**
  - HDA Strategies definition (Lunar, Mars and Phobos landing)
  - Image processing and Data Fusion
    - hybridisation of visual and LIDAR data
    - deterministic, probabilistic and AI-based,)
  - Hardware implementation (CPU, FPGA and CPU-FPGA combination)
- **Internet of Things** (National/EU-funded R&D, ESA):
  - uC, Arduino, ARM, Intel Atom-based (CPU-only)
  - Zybo and Parallella (CPU+FPGA) → focused on Vision-Aided GNC
  - MEMS sensors, open-source GPS RTK
  - (other)Ultimaker





Typical GNC Development Cycle

- **Initial GNC algorithm Development:** FES-based
  - Full onboard system simulation
  - Detailed dynamics, kinematics and environment
  - XML-based configuration
  - Large set of consolidated software modules
- **Migration to C-code** once algorithms mature
  - **Development tool chain**
    - Linux/RTEMS OS, Eclipse IDE, gcc/gdb
  - **SVF tool:**
    - Similar arch. to FES + PIL capability Wireless link to GS
- **Adaptation to flight hardware** where required
  - Algorithm testing/tuning with real flight sensor data
- **Flight testing**
  - Open loop testing (algorithm running in background)
  - Closed-loop (algorithms take control)



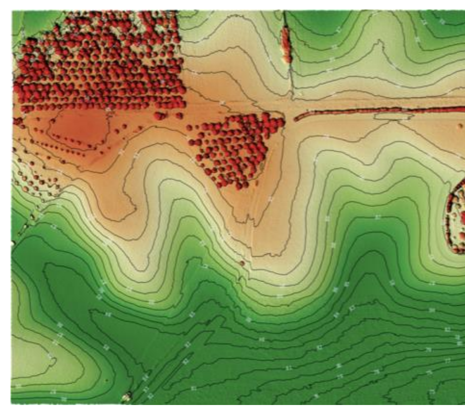
UAV GNC Development

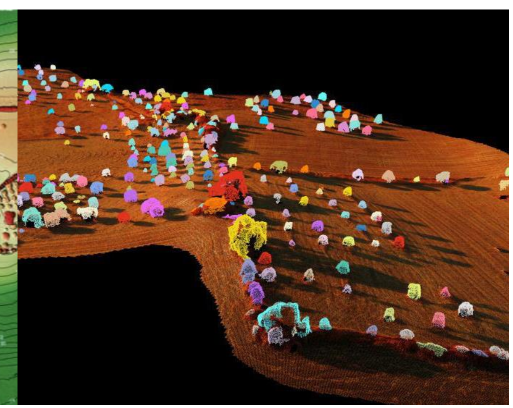
S20 µDrone GNC

- **UAVSIM** (FES, SVF)
  - Based on MATLAB/Simulink
  - Initial simulation framework + model library development
  - Used in GNC development and testing
    - GNC parameter tuning
    - Test of post-flight trajectory reconstruction utilities
    - Generation of artificial sensor data (IMU, GPS, VIS/NIR)
  - Real-time version produced for pilot training
  - Wireless Two-way link with Ground Station
    - Communications link testing (including w/ operating engine)
    - Ground segment SW testing
    - Ground test of in-flight remote GNC parameter update
  - Outcome: Fully autonomous S20 micro-drone flights

S20 µDrone Data Services

- **Operations**
  - Quick response time (<1wk from request)
  - Regular campaigns during crop cycle
  - High productivity (>500 ha/UAV/day)
  - Cloud processing + fast data product delivery
- **Data Products**
  - **Mapping:** 3D Reconstruction
  - **Precision Agriculture:** NDVI charts
    - irrigation/fertilization needs
    - early disease detection
    - increased productivity
    - reduced crop loss
  - **Forestry:** Tree segmentation
    - Estimation of "standing carbon"
    - Measure tree growth over time



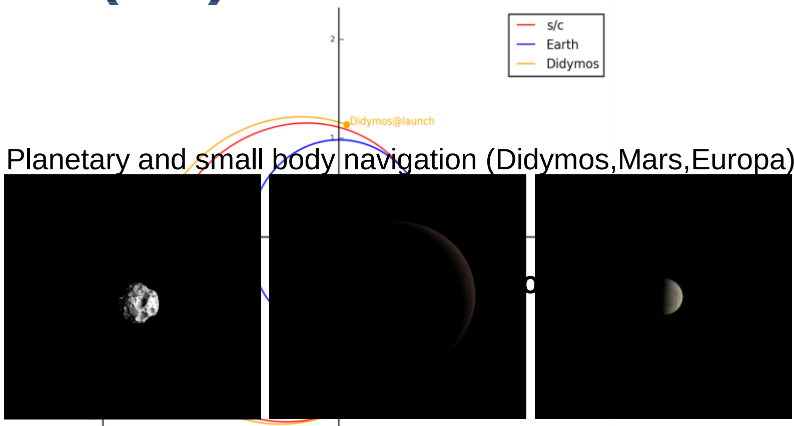


Space GNC Development

Optical Navigation for Space Applications (1/3)

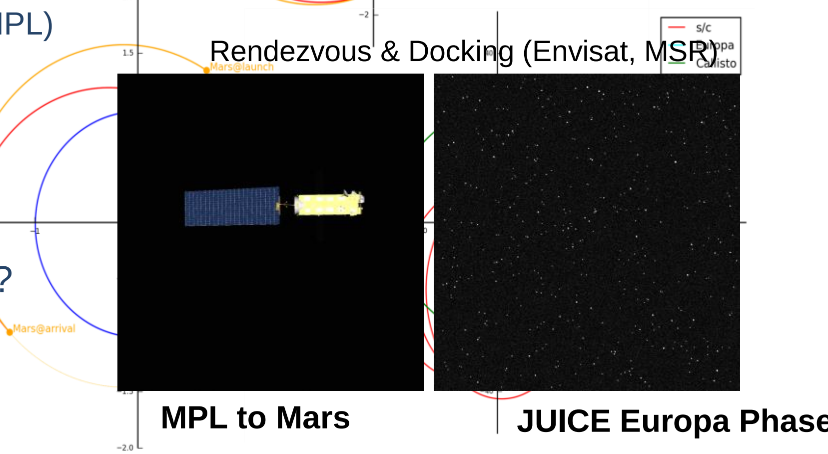
- Project Overview

- Multi-mission OpNav avionics HW development up to TRL4
- Consortium led by JOP (w/ Spin.Works, Airbus SAS)
- Ongoing ESA contract. Applications:
  - Planetary Approach (Luna-27, Luna-Resource, JUICE, MPL, INSPIRE)
  - Small Body Navigation (AIM, Phootprint)
  - Rendezvous and Docking (In-orbit servicing, ISS RdV, MSR, ADR)
  - Descent and Landing (AIM, Phobos SR, Luna-27, Luna-Resource, MPL)



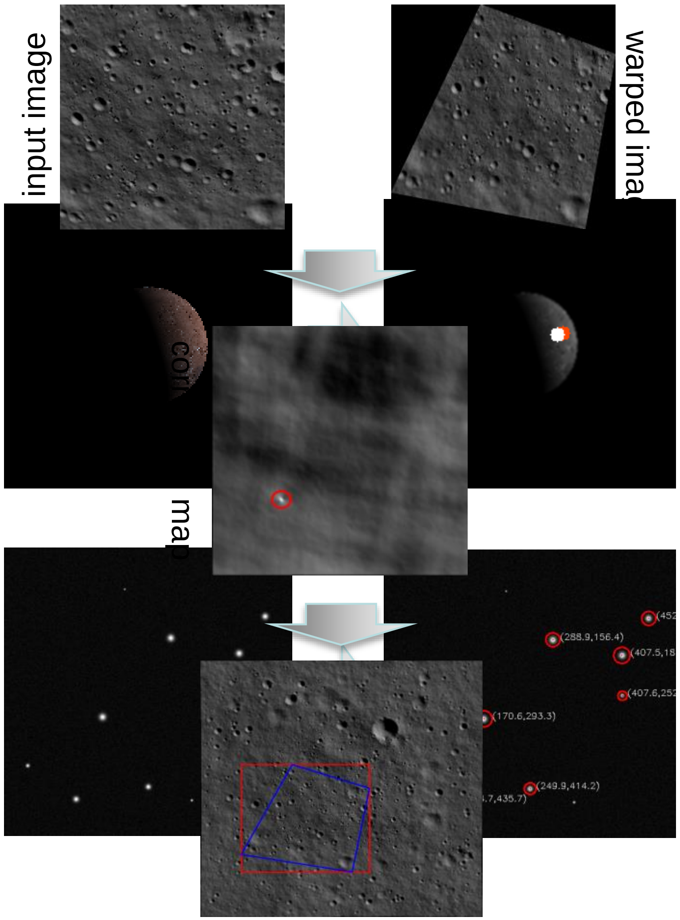
- Technology Developments

- **Which IP algorithms** can be useful for each mission?
- What is the feasibility of each algorithm for space apps?
- How to make the algorithm real-time capable (e.g. CPU/FPGA)?
- **How to validate** each algorithm under realistic conditions?



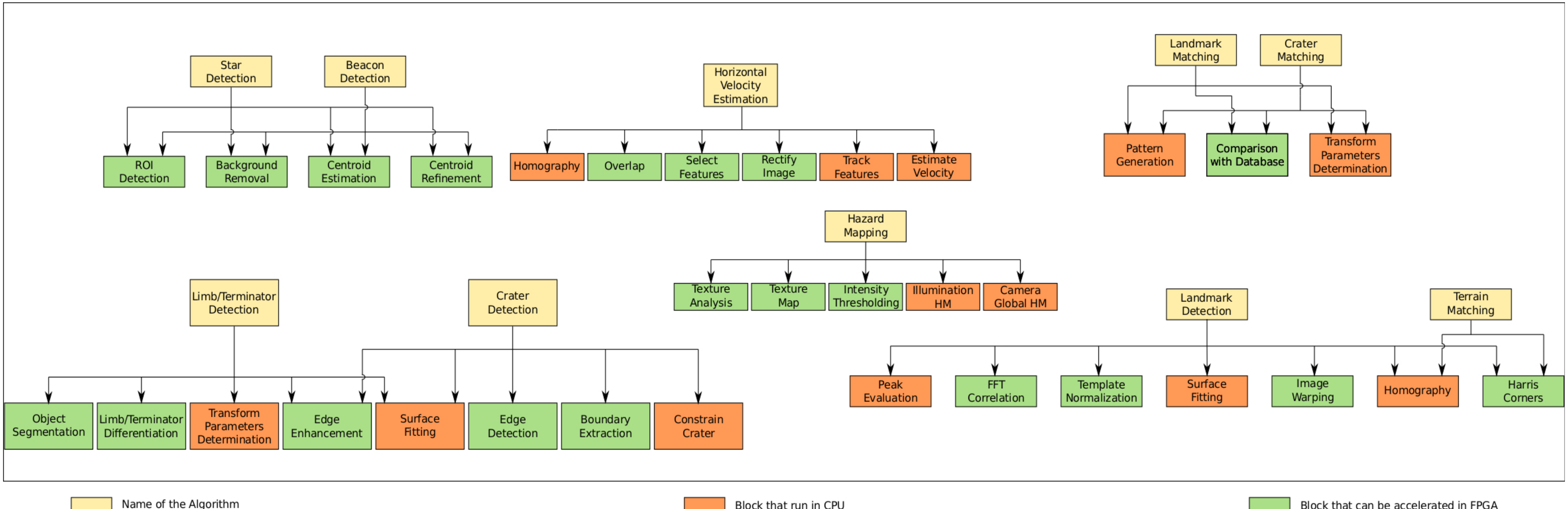
Optical Navigation for Space Apps (2/3)

- **Open Source/Free Software/Hardware Involved**
  - Image Processing Development Tool chain:
    - **OpenCV** image processing libraries
    - **Eclipse IDE**
    - **gcc, gdb**
  - Mission trajectory data: public data + **PyKEP/PyGMO** tools
    - **JUICE Jupiter Tour** (numerical correction)
    - **Lunar landing** powered guidance optimization
    - **MASCOT-2 deployment** phase optimization with multiple constraints
  - Visualization SW
    - Stars, full/partially lit planets, asteroids, spacecraft
    - **JPL Ephemerides** (some body parameters from SPICE)
    - **Freely available Star Catalogs**
    - **XML-based data exchange** (instrument config, IP setup, test config)
    - **VTK7.0, OpenCV-based visualization** (most scenarios)
      - Exceptions: ESA PANGU for SB Navigation, D&L



a priori map w/ correlated image

GNC Technology Development: Space Exploration Examples (1)



	Algorithms									
Block Name	Star Detection	Beacon Detection	Limb/Terminator Detection	Landmark Detection	Landmark Matching	Crater Detection	Crater Matching	Terrain Matching	Horizontal Velocity Estimation	Hazard Mapping
2D Convolution	✓	✓	✓	✓		✓		✓	✓	
Detect Max and Min	✓	✓	✓							✓
Threshold	✓	✓	✓							✓
Comparison					✓		✓			
Histogram			✓							✓
Mean + Variance								✓		✓
Connected Components						✓				
FFT								✓		

- Tests performed in the scope of "Navigation-on-a-Chip" activity

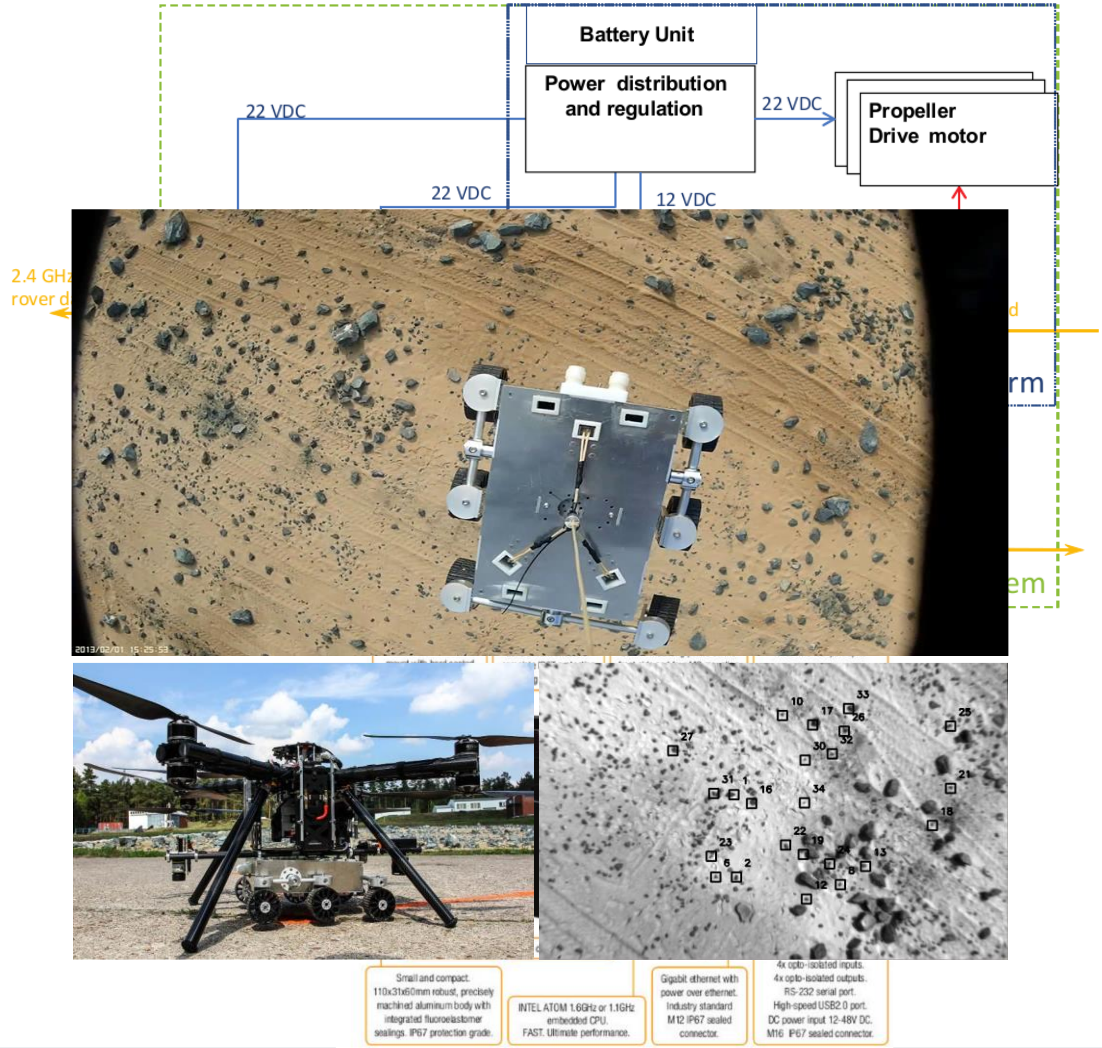
StarTiger Dropter

- Project Overview

- Flight Demonstration of a Skycrane-like Rover deployment from a hovering Mars Landing vehicle (TRL 4/5)
- ESA contract (StarTiger, 2013-2014)
- Consortium led by Airbus DS (DE), with DFKI (Bremen,DE), IAII (Poznan,PL), Spin.Works
- Scenario: Mars Precision Lander

- Technology Development Activities

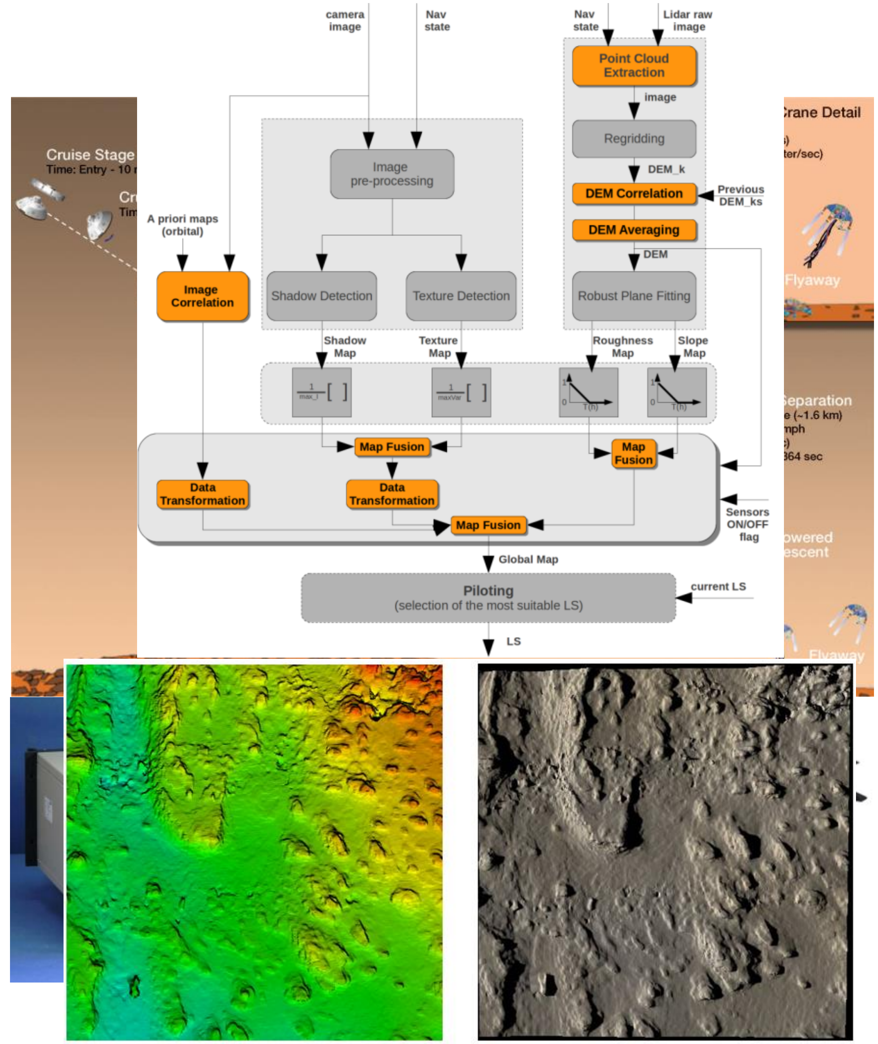
- Descent and landing simulation tool
- Real-time embedded **VBN** using multiple sensors:
  - Inertial Measurement Unit,
  - Range measurements,
  - Image-based observations
- Real-time visual **Hazard Avoidance** system



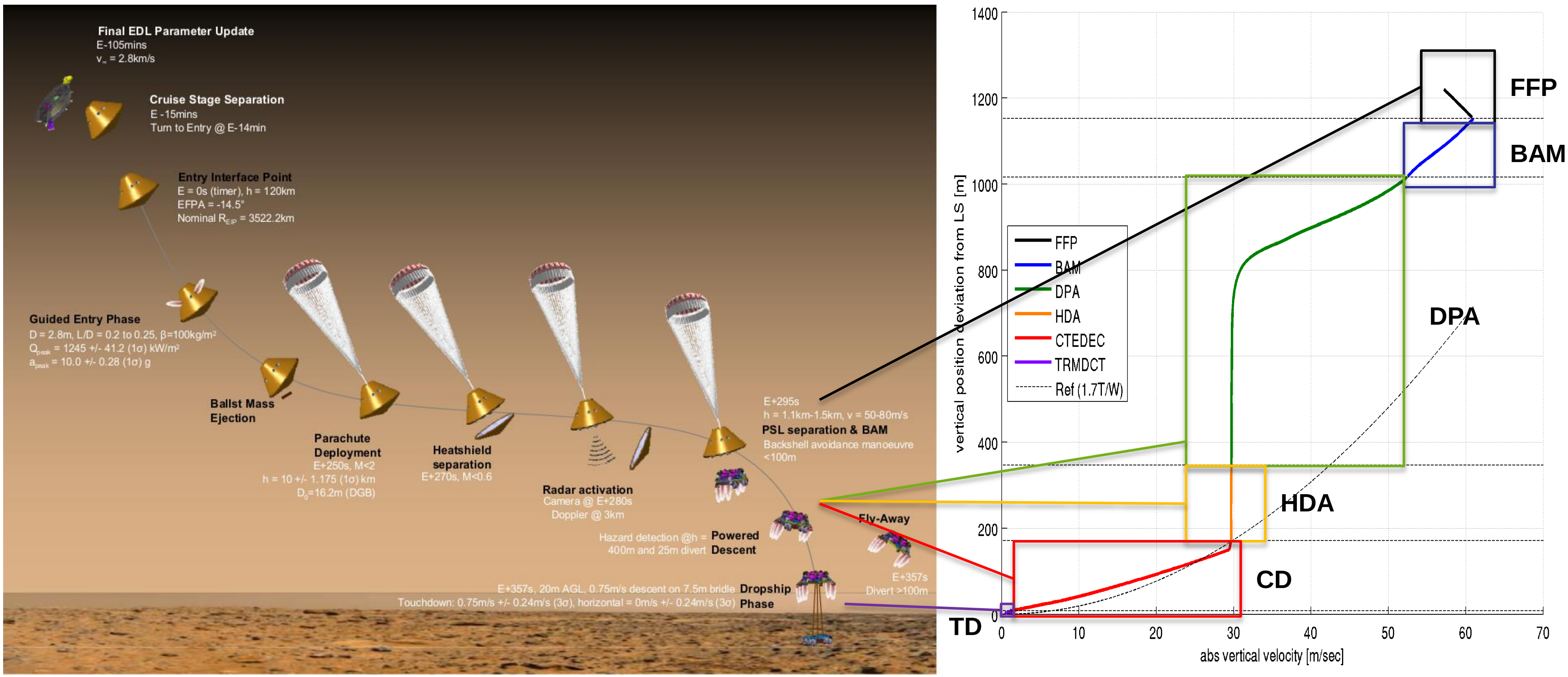
GNC Technology Development: Space Exploration Examples (3)

AVERT (AVoidance Algorithms development and Extended Testing)

- **Project Overview**
  - Data Fusion Processor development and in-flight demonstration (up to TRL 5)
  - ESA MREP-2 Activity (2015-2017)
  - Spin.Works is prime contractor (w/ UNINOVA+Irida Labs+RUAG-SE)
- **Technology Development Activities**
  - Hardware-in-the-loop simulation (based on lab control hardware laboratory at TEC-ECN)
  - Hardware-accelerated **Vision-aided Navigation** and **Hazard Avoidance**
  - Real sensors (Camera, Lidar) and space-qualified hardware (PLDPU – RUAG-SE)
  - Tests over representative terrain (lab + Mars Analog)



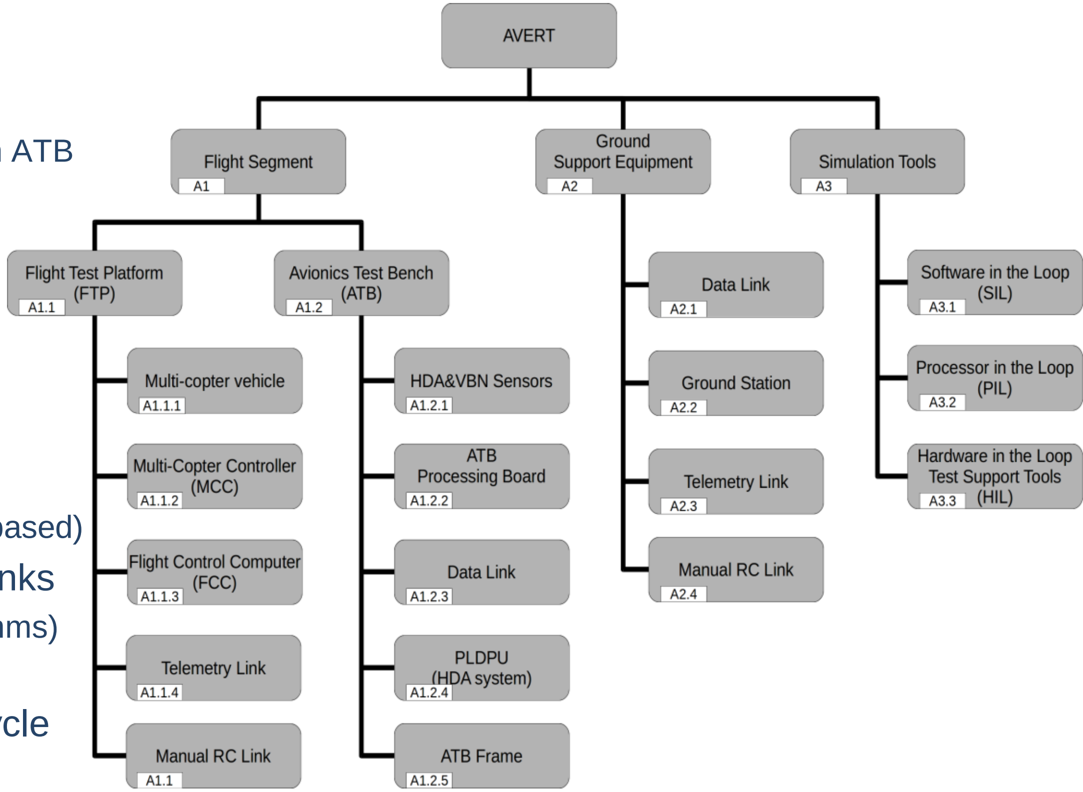
AVERT Mission: Mars Precision Lander



AVERT Avionics (1/2)

- Overview

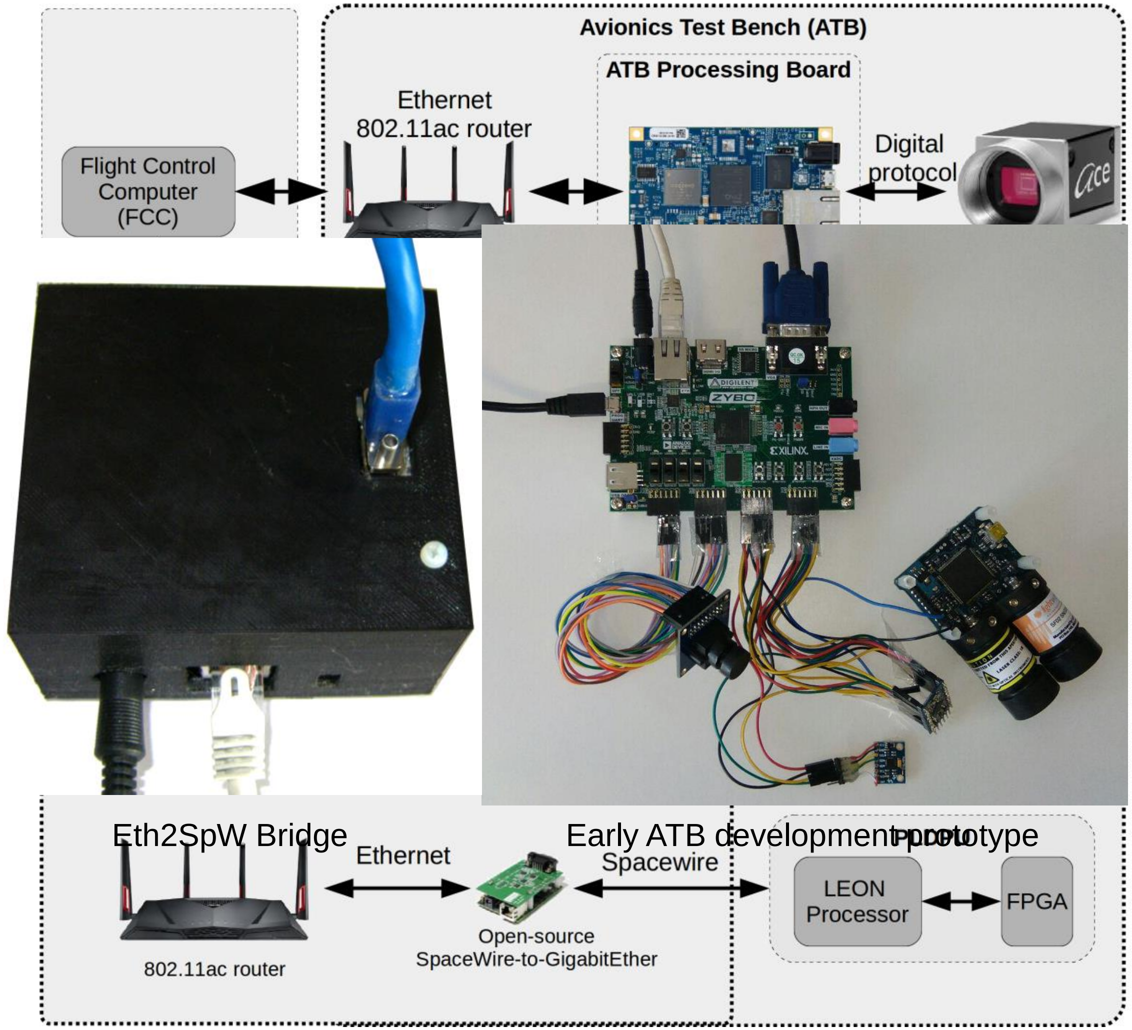
- Flight Platform is heavy multicopter (~20kg)
    - Platform avionics are completely independent from ATB
    - Multi-copter controller: Flight Control
    - Flight Control Computer: Guidance, GPS-INS Nav
    - ATB telemetry link
    - Pilot control during take-off, transfer to test terrain
- ATB carries complete VBN+HDA experiment
    - Sensor (visual camera + HDA)
    - Processing board (ATB-PB)
    - Data links with PLDPU (HDA processing, ground-based)
- GSE allows real-time monitoring, PLDPU data links
    - Relay service (only allows 2-way ATB-PLDPU comms)
    - Visualization of telemetry data from FTP, ATB
- Simulation tools accompany full development cycle
    - Demonstration of HDA+VBN concept validity (SIL)
    - Groudn Verification of HW implementation (PIL)
    - Flight test planning, preparation and post-flight verification



AVERT Avionics (2/2)

- ATB Hardware

- Processing Units:
  - Zynq-based CPU+FPGA
  - MREP PLDPU
- Sensors
  - Lightware Laser range finder
  - Velodyne Scanning Lidar
  - Basler 1.3MP computer vision camera
  - High-accuracy MEMS-based IMU
- Communication links
  - Long range Wi-fi link for telemetry/data
  - Local ethernet-based router
  - Ethernet-to-SpaceWire bridge for PLDPU interface
  - Telemetry and landing site designation through ethernet link with FCC



Technology and Market Trends Relevant to future GNC R&D

Relevant Enabling Technologies (1/2)

- **Ubiquity of Mobile Technologies**
  - Highly miniaturized
  - Reliable and low-cost
  - High-performance (although specialized in video and communications)
  - Diversity of hardware components: sensors, processing units, communications, storage
    - Processing hardware: MultiCore, FPGAs and DSPs
  - Growing adaptation of available hardware to specialized fields (and in particular to drones)
- **Open Source/Free Software and Hardware**
  - Operating Systems (e.g. Linux, RTEMS)
  - Integrated development environments (e.g. Eclipse)
  - Linear Algebra tools (e.g. LAPACK)
  - Visualization software (e.g. VTK) and image processing software (e.g. OpenCV)
  - Ephemerides, Mission Planning and Operations-related Utility Toolkits (SPICE, PyKEP, PyGMO)
  - IP Core Libraries
  - Mission planning, flight control and operational tools for commercially available Drones (APM)

Relevant Enabling Technologies (2/2)

- **Commoditization of Test Platforms**
  - Availability of HIL/PIL facilities based on common simulation tools (e.g. MATLAB/Simulink)
  - Robotic Arm Facilities
    - Scaled environments
    - Testing of D&L, RVD and ADR missions
  - Drones (fixed, rotary-wing)
    - Applied to D&L missions
  - CubeSats
    - Earth Observation + Global Comms
    - Deep Space
- **Current Obstacles for inclusion in Future Exploration Missions**
  - TRL, TRL, TRL...
    - Avionics and autonomy
    - Communications (especially from deep-space)
    - Propulsion
    - Power generation

Recent Market Developments

- **Emergence of Small, Micro and NanoSats**
  - Miniaturization of components (general trend, especially originating in mobile technology)
  - Direct use of COTS components for orbital missions (sensors, processors, comms, storage)
    - Appearance of companies exclusively dedicated to production of standard packages
  - High-resolution imaging satellites from Low Earth Orbit:
    - SSTL-300 and Satrec SI-300 (300kg-class): 1m/pixel (DMC-3, DubaiSat-2, Deimos-2)
    - PlanetLabs Dove (<5kg): 3-5m/pixel
  - Appearance of ‘megaconstellation’ concept
    - Mass production of small, ultra-low-cost (highly COTS-based), ‘expendable’ sats for global coverage (imaging, comms)
    - Use of data analytics techniques for value extraction
- **Shared Small/Micro/NanoSat launch services + mission opportunities**
  - Launch of large numbers of small/micro/nanosats as add-ons to launch of large satellites
  - Installation of in-orbit deployment facilities at ISS (JEM J-SSOD, NanoRacks NRCSD)
  - Ongoing development of dedicated small sat launchers
  - Mission opportunities for NanoSats coupled with exploration: NASA Insight and SLS EM1, ESA AIM

Accelerating GNC-Related Technology Development

Low-Cost Technology Demonstrations for Exploration (1/2)

- **Problem:** Large gap between Lab and in-flight demo of exploration-related GNC technologies
- **Concept:** Nanosat or MicroSat-based forward demonstration of key enabling technologies for exploration
- **Guiding principles:**
  - Use **every ESA deep space mission** to support nanosat-based tech demos
  - No tech demo shall be allowed to increase mission risk
  - Probability of failure to be minimized, but ultimately acceptable (larger risk-taking for larger returns)
  - Priority attributed according to long-term programme analysis (criticality, relevance, feasibility, impact):
    - Technologies affecting higher number of upcoming missions are preferred
    - Tests which eliminate technology obstacles to enable new classes of missions or technologies are preferred
    - Tests for which terrestrial laboratories are inadequate are preferred
    - Tests for which results are more likely to succeed or provide unambiguous results are preferred
    - Scaled tests where applicability of results to full-scale missions is not questioned, are preferred
  - Per mission cost targets: ~10MEuro (similar to Insight MARCO)
- **Main Goal:** accelerate pace of innovation in exploration

Low-Cost Technology Demonstrations for Exploration (2/2)

- **Suggested ESA involvement:**
  - Selection of key enabling technologies for further investigation (e.g. Aurora Technology Dossier, MREP Technology Roadmap, etc)
  - Support to set up dedicated integration laboratory (similar to JPL?)
  - Support to find flight opportunities aboard larger missions
    - Recent examples at ESA: COPINS, LUCE, RVD Experiments
  - Survey of Nanosat-based components, development resources, missions and developers
    - Components survey (and corresponding track record): processing hardware, sensors, actuators, comms
    - Survey of open-source SW and HW resources
    - Characterization and classification of mission profiles
    - CubeSat developers: which are most often used, where, how and why?
  - Support to inclusion of CubeSat/MicroSat dispensers on every deep space mission (incl. Flagships)
    - Mission opportunities for NanoSats coupled with exploration:
      - NASA Insight (2x3U CubeSats for EDL data relay)
      - SLS EM1 (12 CubeSats for Lunar exploration)
      - ESA AIM (2 CubeSats for joint asteroid observation)

Example Tech. Demo. Missions for Exploration

- Mission Profile

- Planetary Aerocapture or EDL Demo (including pinpoint entry)
- Small body (NEO, Asteroid, Comet, small planetary moons, planetary ring components) exploration (including orbiting, active landing, hopping)
- Deep-space Nanosat-based high rate communications (miniaturized deployable HGAs)
- Planetary communications + navigation infrastructure deployment
- Forward terrain characterization of unknown environments for landing missions
- Formation-flying missions to planets
- Testing of new miniaturized instrumentation (VIS/IR/MS/HYP cameras, SAR instruments, inertial sensors, actuators)

- Impact on Avionics

- Increased autonomy is essential – but important to choose the right functionalities to focus
- Additional services required from “main” spacecraft (typ. long-range comms support)
- Processing needs tendentially higher – important to manage resource-hungry processes (IP)
- Lowest possible power consumption – low-rate processing except where inevitable

Example Concept: Deimos Exploration

- **Main Spacecraft:**
  - Mars orbiter and/or lander
- **Mission Sequence:**
  - Ride along with orbiter to Mars
  - Separate a few days prior to MOI
  - Perform aerocapture (use atmospheric pass to change plane, enter highly elliptical orbit)
  - Impulsive manoeuvres to reach Deimos (several 100s of m/s)
  - Use active landing legs to absorb ground impact
  - Hop to new locations whenever required
  - Jump to orbit where
- **Foreseeable challenges**
  - Guided aerocapture (requires dedicated demo mission; see AeroFAST/FP7)
  - MicroSat propulsion (see CleanSpace-related TDA)
  - Active landing legs (see MREP TDA)

Example Concept 2: Multiple Tech. Demo for EO/Exploration

- **Main Spacecraft:**
  - 16U CubeSat or dedicated MicroSat
- **Mission Concept:**
  - ISS or shared launch to LEO/SSO
  - Focused on Earth Observation, but with several payloads targeted towards exploration missions
  - Simultaneous in-flight qualification of multiple technologies as payloads:
    - Space mechanisms
    - NanoSat propulsion demo
    - GNSS-R sensor
    - SDR-based communications
    - SAR instrument
    - Multispectral camera
  - Coordinated ground operations for the platform at single location
  - Each team is afforded access to their own payload data on a time slot basis; processing is then the responsibility of each team

Conclusions

- GNC Development Cycle predicated on availability of end-to-end testing tools
  - Numerical simulation tools (esp. FES, SVF) have become sufficiently widespread as to be an essential GNC development tool, for both UAV and Space projects
  - Emergence of specialized free open-source software for an entire development tool chain, as well as for operations such as linear algebra, image processing and visualization are dramatically accelerating prototype development, test and validation, allowing extended experimentation (including on real HW) prior to committing to specific designs
  - Embedded COTS hardware can be made to operate through similar interfaces as in space missions (CANbus, SpW), making incremental evolution possible from COTS hardware to fully space-qualified HW
  - Progress towards higher TRL (all the way to in-flight demonstration) is being made easier through widespread availability of test tools, platforms and technlologies
- Current Technology and Market Trends favour increasing use of Micro- and NanoSats
  - Miniaturization trends and near-universal use of COTS hardware for in-space demonstrations
  - Emergence of a constantly evolving ecosystem of Nano and MicroSat hardware, launch service providers + deployment facilities is helping democratize access to space experimentation
  - Megaconstellations represent the commercial side of the available opportunities; exploration may be next.

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