Advanced AOCS for Micro/Nano Satellites

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Outline

- What is micro/nano satellite ?
- What are the needs on AOCS of micro/nano satellites ?
- AOCS solutions at component level
- AOCS solutions at system level
- Review

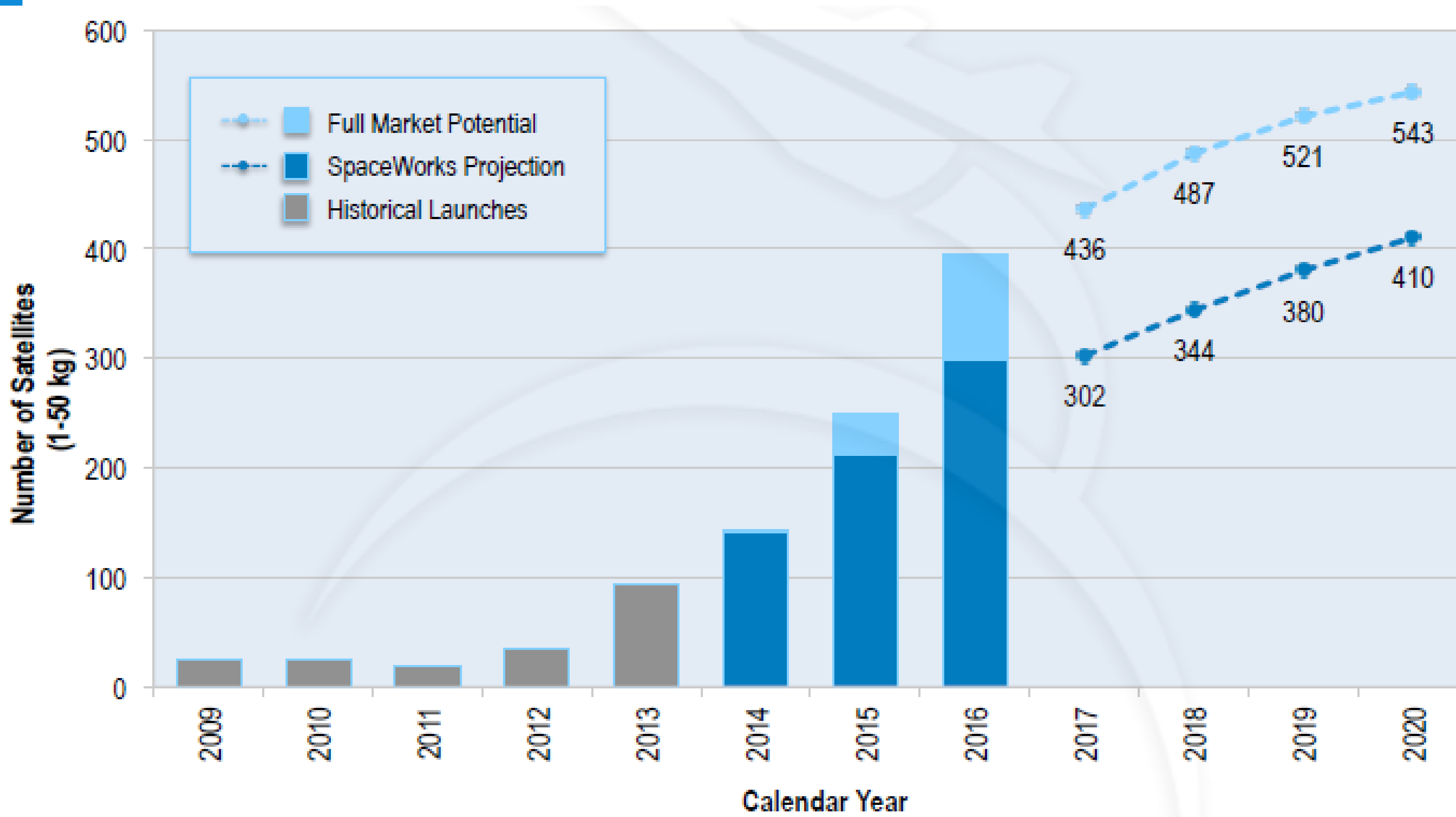
What is micro/nano satellite ?

Categories of Small Satellites

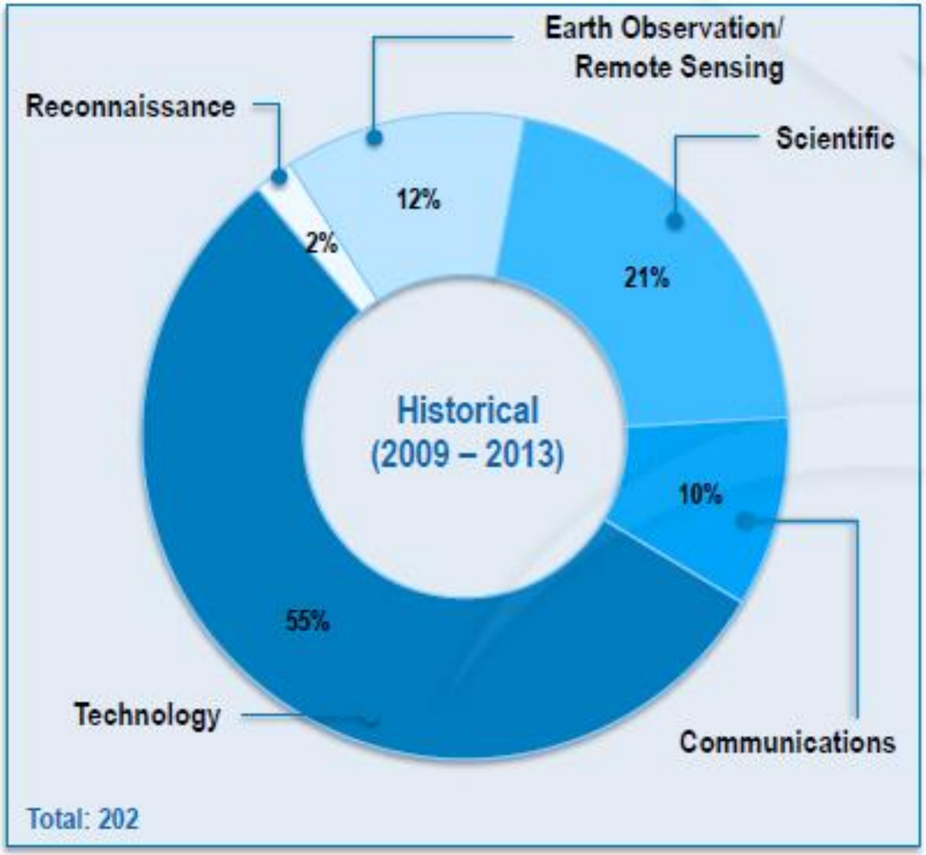
Category of Small Satellite	Mass Range (kg)	Typical Applications
Mini-Sat	100 - 1000	High-end EO, small GEO, other high demanding missions
Micro-Sat	10 - 100	Low-end EO, science, tech-demo
Nano-Sat *	1 - 10	Tech-demo, low-end science
Pico-Sat	0.1 - 1	Tech-demo
Femto-Sat	< 0.1	?

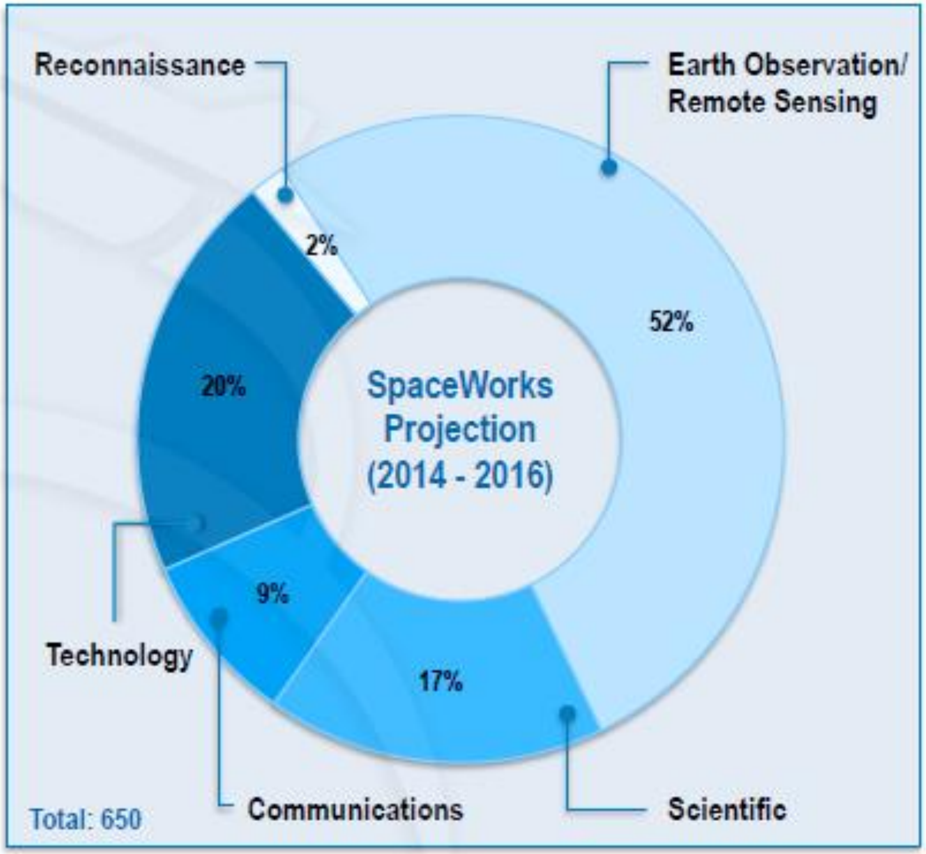
* CubeSats typically fall into the category of nano-sat from the mass point of view, but they do not belong to any of these categories

Launch History and Projection



Application Areas

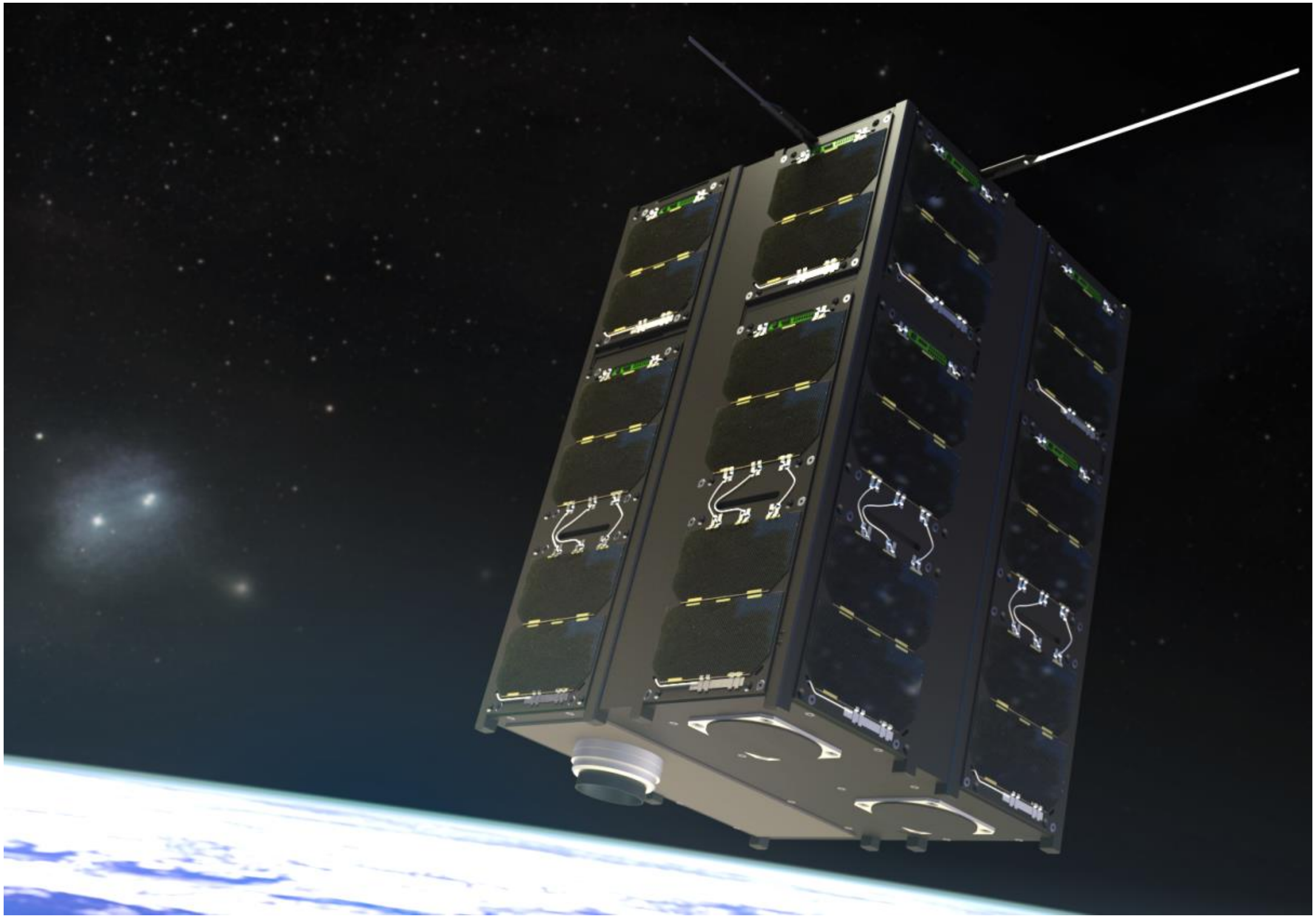




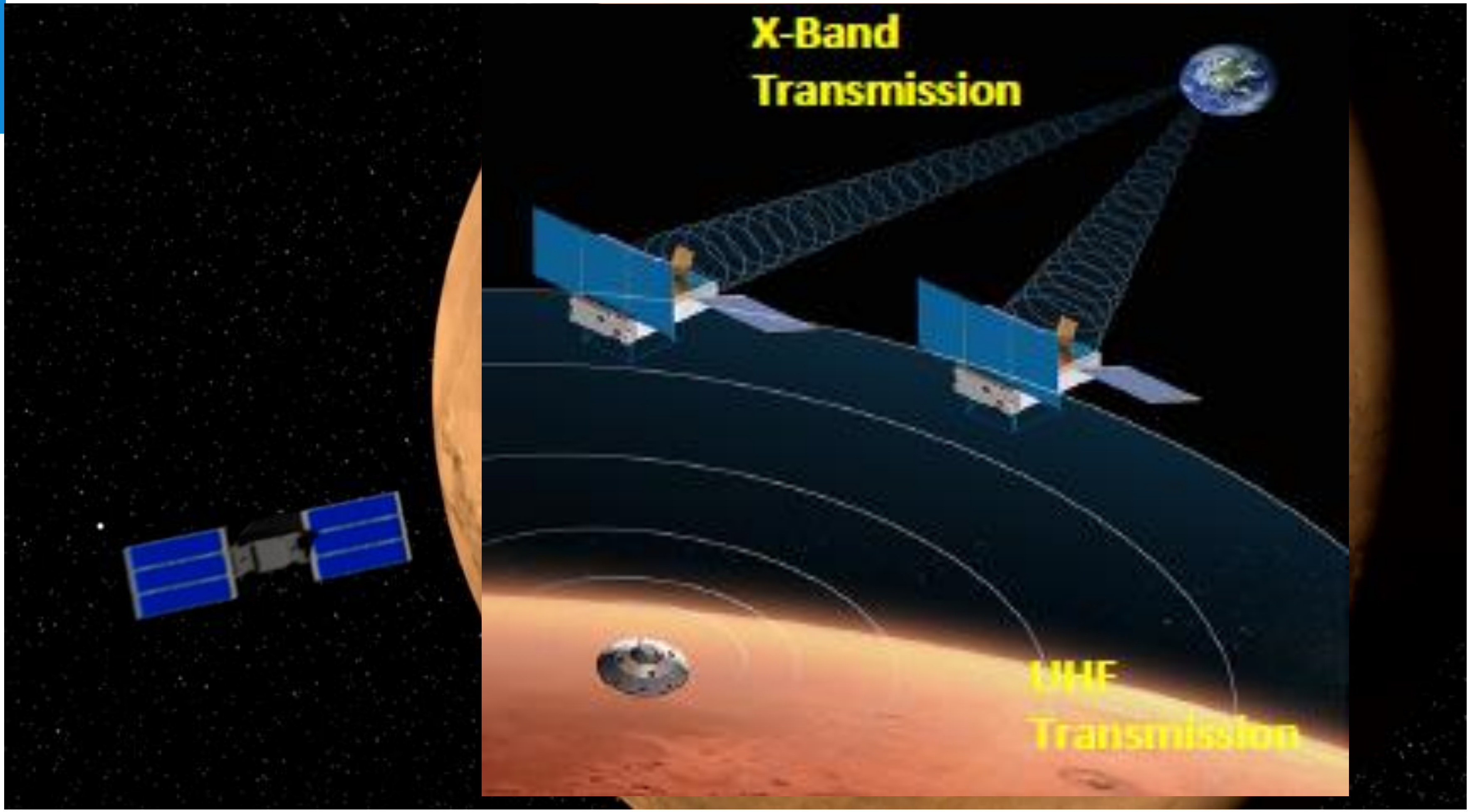
ADR Precursor – CADRE 1

DOVE & Flock

Agricultural Monitoring System



Deep Space - MarCO



What are the needs on AOCS of micro/nano satellites ?

What Do Users Want ?

Performance vs. Low cost

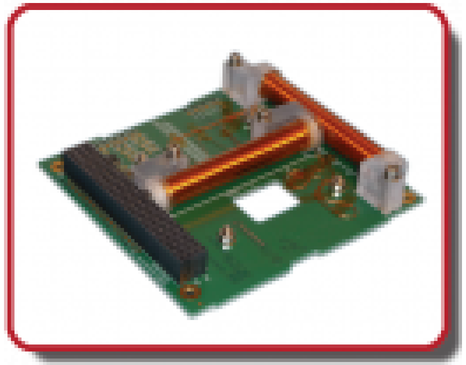
No universal answer
Low cost get priority for satellite < 50 kg

Typical ADCS Needs

Sat. Mass (kg)	Attitude (deg)		Orbit control	Typical applications
	Acknowledge	Control		
10 - 50	0.01	0.05	Yes	Science, Tech. Dem, EO
3 - 10	0.1	0.5	Yes	Low-end science, Tech. Dem
< 3	0.5	1 - 5	No	Experiment

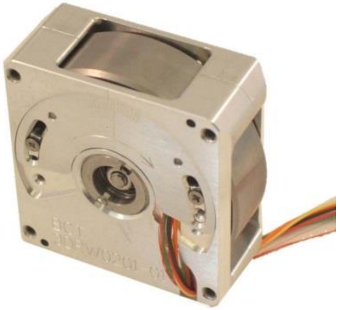
Actuators for Different ADCS Modes

- Detumbling
  - Open loop control, gyro is good to have
- Attitude stabilization
  - Passive attitude stabilization
- - permanent magnet and hysteresis rods
- - simple, low cost and no power consumption
- - tumbling over poles
- - difficult to use a magnetometer
  - Active attitude stabilization
- - Thruster: only as payload instead of actuator
- - Magnetorquers: no better than 5 degrees accuracy



Actuators for Different ADCS Modes

- Wheels:
  - Need to be de-spun
  - Difficult to arrange three wheels and combined three magnetorquers
  - Mounting one momentum wheel along one axis be a good compromise between weight and accuracy
  - However, limits the maneuvering capability due to gyroscopic rigidity



Sensors for Micro/Nano Satellites

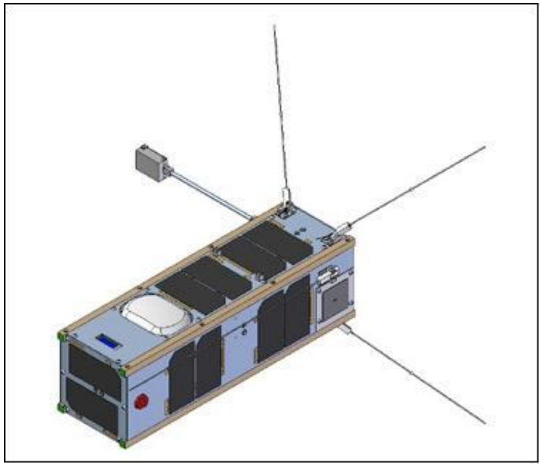
- Magnetometer
  - Heavy computational load and easy interfere by the surrounding environment
- Sun sensor
  - Changes with temperature and it is inaccuracy when the Sun light is close to parallel direction
- Gyro
  - Suitable for adding additional accuracy to rest attitude sensors instead of providing absolute attitude

ADCS of In-orbit Micro/Nano Satellites

Spacecraft	Format	Launch Year	Mission	MM	Gyros	PD	ES	Fine SS	STR	MTQ	RW	PAS
COMPASS 1	1U	2008	Demo	X		X				X		
Swisscube	1U	2009	EO	X	X			X		X		
e-st@r	1U	2012	Demo	X	X	X				X		
Triton-1	3U	2013	Demo	X		X				X		
GeneSat-1	3U	2006	Sci									X
TechEdSat	1U	2012	Demo									X
UniCubeSat-GG	1U	2012	Sci	X(2)		X						
Strand-1	3U	2013	Demo	X			X	X		X	X	
CanX-2	3U	2008	EO	X				X		X	X	
AAUSAT-II	1U	2008	Sci	X	X	X				X	X	
Delfi-n3Xt	3U	2013	Demo	X		X				X	X	

Flight Results Review

- Relatively high pointing accuracy (CanX-2)
- Around 2 degrees
- Combination of fine Sun sensor and magnetometer. Pointing knowledge of 0.05 degree
- Reaction wheels were used, and a residual ripple noise of 1uNs caused by them.



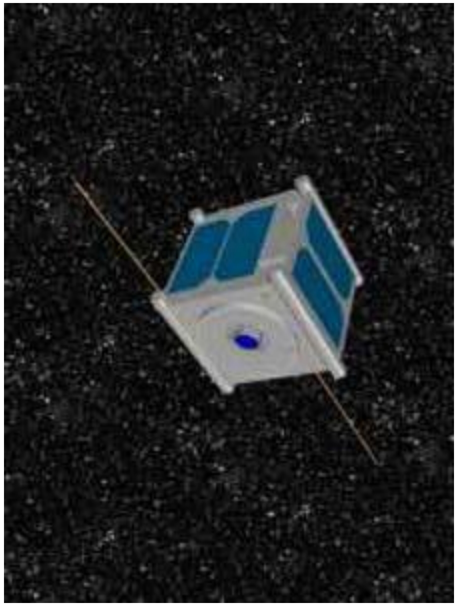
Flight Results Review

- Lessons learned:

Swisscube

- ❑ Onboard gyros should have large dynamic ranges
- ❑ Fully calibration on sensors and actuators
- ❑ Enough time given for the decay of magnetic field caused by magnetoquers before taking magnetometer readings
- ❑ Be careful with phase difference between measured B-dot and the real value

Flight Results Review



- AAUSAT
  - Never commissioned and did not enter a real operational phase
  - Primarily down to weak communication link
  - Weak communication link was also caused by fast tumbling

- Question: Set up communication first or detumbling first?
- Answer: B-dot is turned on by schedule if communication link cannot set up properly after several pass

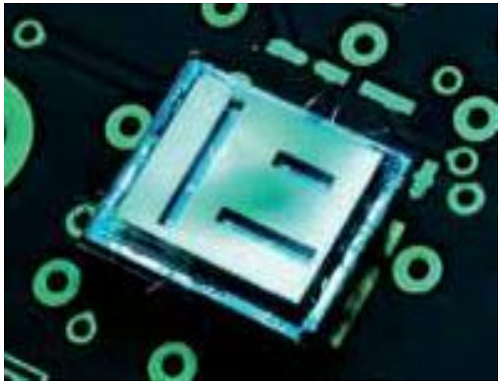
- Gap between state-of-the-art and future needs on AOCS
- Scientific and Earth observation missions require high performance AOCS!

Solutions – Component Level

MEMS Sun Sensors

MEMS 2-axis Sun sensor of DTU

- 7mm×8mm
- Accuracy 1° (in ±40°) or 2.5-5° (in ±70°)



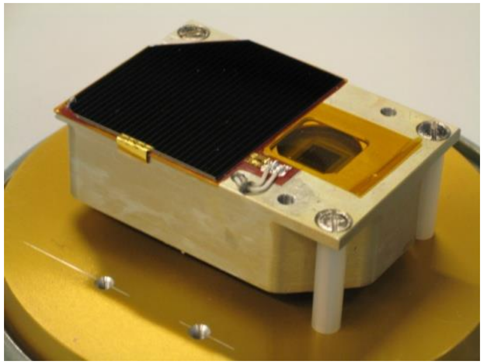
Digital Sun sensor on a chip of Selex Galileo

- Image sensor, processor & interface electronics are on the same chip
- 60 grams, 0.2 W, 30mm×30mm×25mm
- Accuracy 0.02° (in ±64°)

Dialogue Sun Sensor

Autonomous Wireless Sun Sensor (AWSS) of TNO

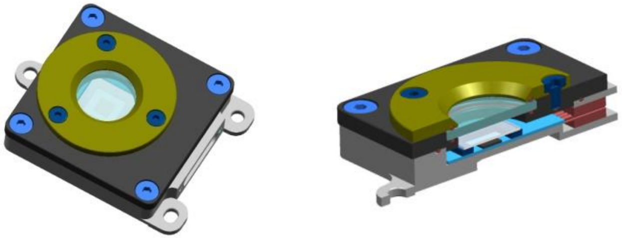
General Specifications	
Sensor Type	Quadrant Sun Sensor
Mass	80 g
Dimensions	60x40x20 mm (lxwxh)
Field of view	90° x90°
Inaccuracy	~ 1°
Data rate	1 Hz



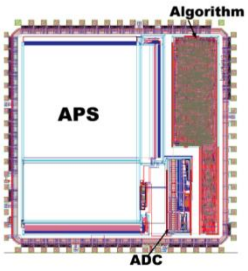
RF Specifications	
Frequency	915.0 MHz
Modulation	Gaussian Frequency Shift Keying (GFSK)
Bitrate	150 kbps (50 kbps effective due to encoding)
Encoding	Manchester
Protocol	Nordic Semiconductor ShockBurst (proprietary)

Digital Sun Sensor

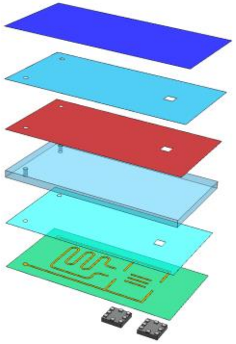
Current and next generation digital sun sensor of TNO



- Key specifications of current development
  - Accuracy 0.1° (3σ)
  - FOV ±47°X±47°
  - Albedo insensitive
  - Average power consumption < 100mW @ 5V input
  - Digital output (UART)
  - Volume 52mmX52mmX14mm excluding mounting
  - Based on APS+ chip (0,18 μm CMOS)
  - Integrated micro connector



- The future: very light (<5 grams), low cost, autonomous configurations (self powered, wireless)



Question

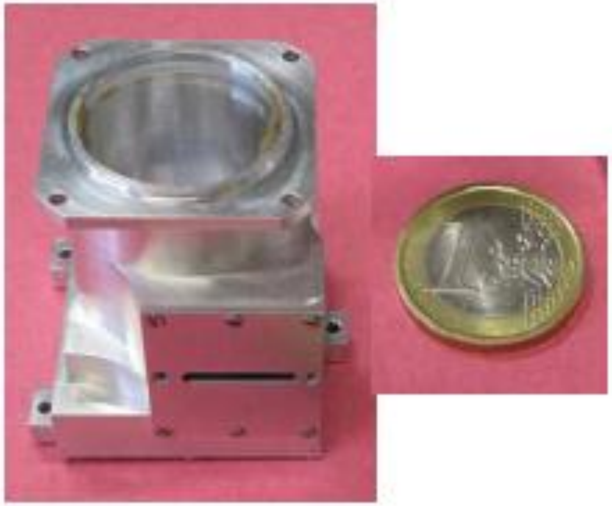
What is the simplest solution of sun sensor ?

Miniaturized Star Tracker

Recall: What is the principle of star tracker ?

MEMS star tracker of Selex Galileo

- Sponsored by ESA NEOMEx programme
- System-on-Chip
- Accuracy 15 arcsec
- 175 grams
- 0.72 W
- 42mm×37mm×83mm



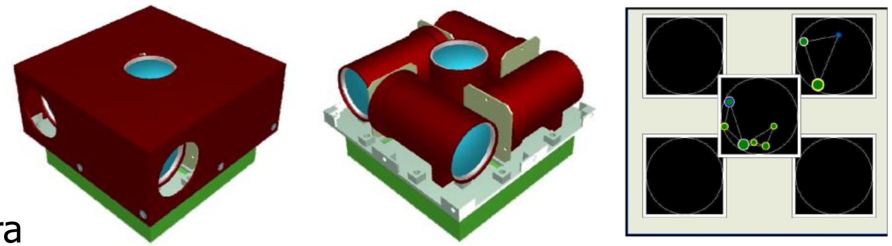
Low-cost star tracker of Berlin Aerospace

- Dimensions $30 \times 30 \times 38.1\ mm^3$
- Mass 50 grams
- Accuracy 30 arcsec
- 0.65 W
- Interface RS485, I2C

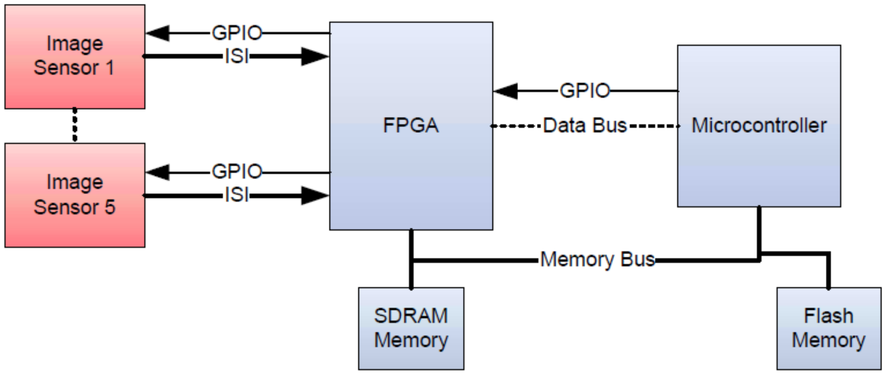
Miniaturized Multi-aperture Star Tracker

Characteristics

- Large FOV and small baffles
- 5 apertures for high availability
- Robust against Sun/Earth blinding
- Star triangles across multiple camera heads improve accuracy
- Low system costs



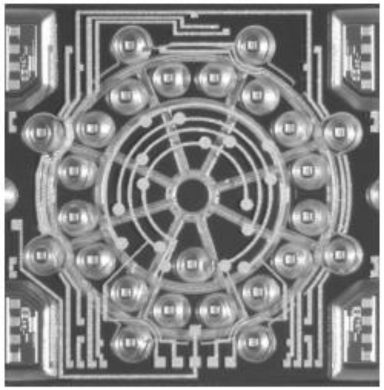
General Specifications	
Success rate	> 95%
Accuracy	0.01º-0.02º (three axis)
Power consumption	< 300 mW (average)
Mass	< 500 grams
Dimensions	100X100X50 mm^3
Life time	3 years (LEO)

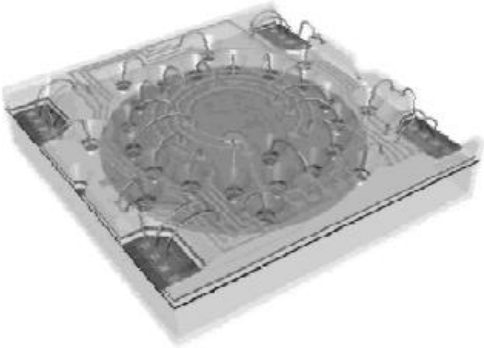


MEMS Gyro

MEMS gyro of Systems Engineering & Assessment Ltd (SEA)

- Uses a silicon ring with a number of capacitively coupled plates
- Flight demonstration on Cryosat-2
- Moderate performance (bias stability < 10° /hour)



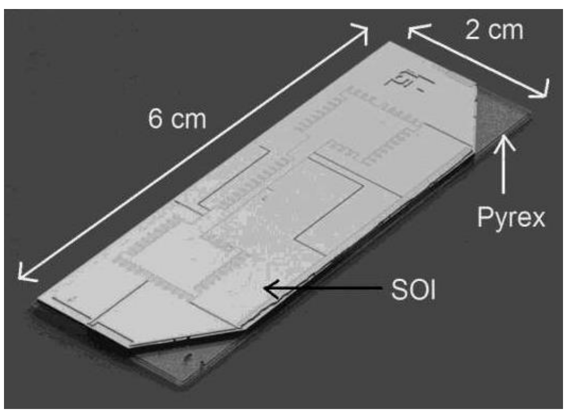


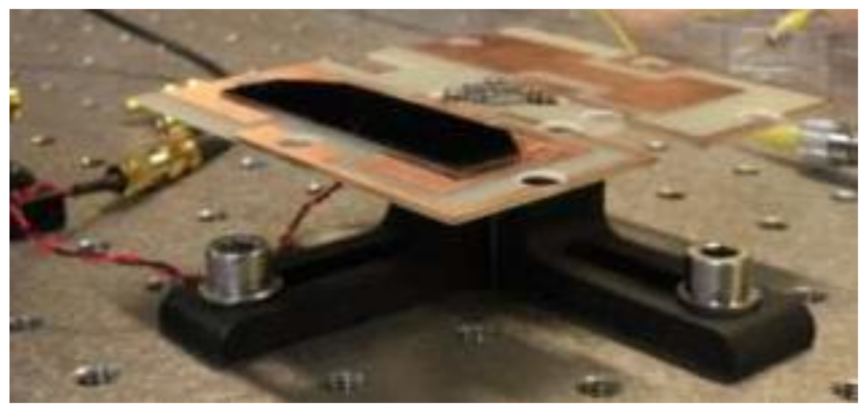
MEMS Earth Sensor

Recall: What is the principle of Earth sensor ?

MEMS Earth sensor of EPFL

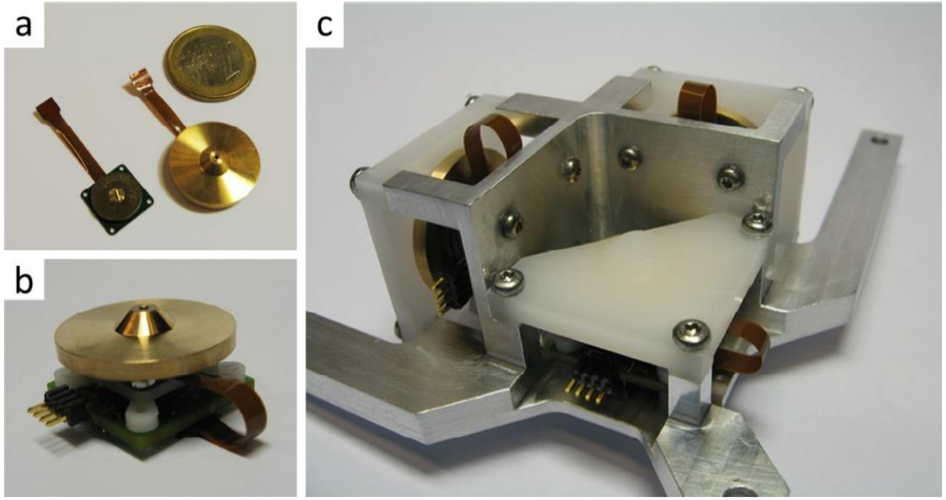
- Directly measures the gravity gradient vector instead of optical information to provide the attitude knowledge
- Eliminates the need for multiple external access ports, allowing a compact sensor
- Accuracy 5°





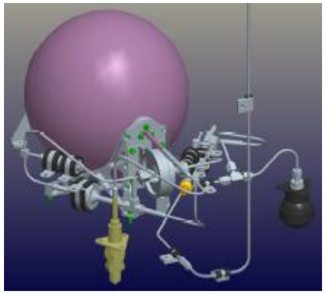
Micro Reaction Wheel

- Developed around a COTS micro-motor
- Replaced lubricant in the motor with vacuum-proof lubricant (Braycote) for vacuum environment
- Maximum torque 0.055 mNm
- Angular momentum storage 1.5 mNms
- Total mass (bracket + 3 wheels) 82 gram
- Peak power consumption 530-710 mW



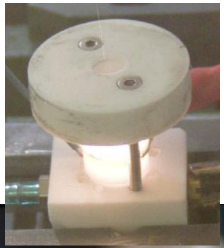
Micro-propulsion

- Cold gas micro-propulsion of NanoSpace
  - Demonstrated on PRISMA
  - Delivers thrust from tenths of micro-Newtons up to a milli-Newtons
  - The golf-ball sized thruster module contains a silicon wafer stack with four complete rocket engines with integrated flow control valves, filter and heaters



©NanoSpace

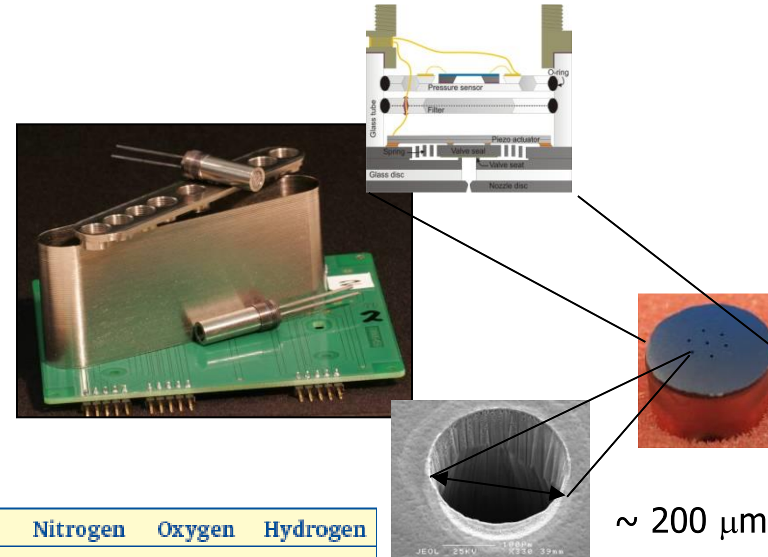
- Plasma-arcjet micro-rocket of Micro-Space
  - Ignites plasma inside the micronozzle for low thrust range and microrocket for larger thrust range
  - 1/10th propellant consumption



©Micro-Space

Solid Cool-Gas Micro-Propulsion

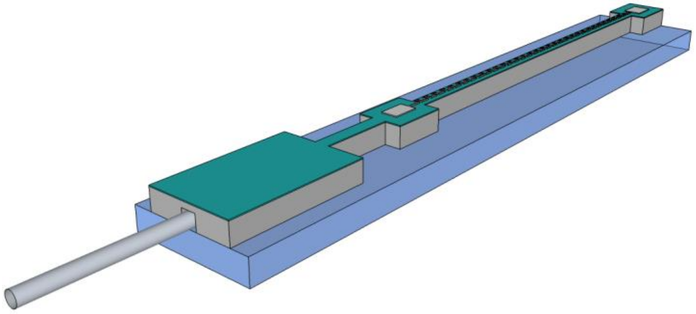
- T³-µPS (TNO, UTwente, TU Delft)
  - Thrust: 1-100mN (scalable)
  - Cool gas generators to limit propellant volume
  - Pressure measurement using strain gages
  - Filter pore size: 5µm

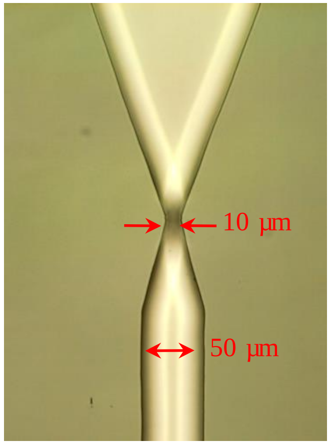


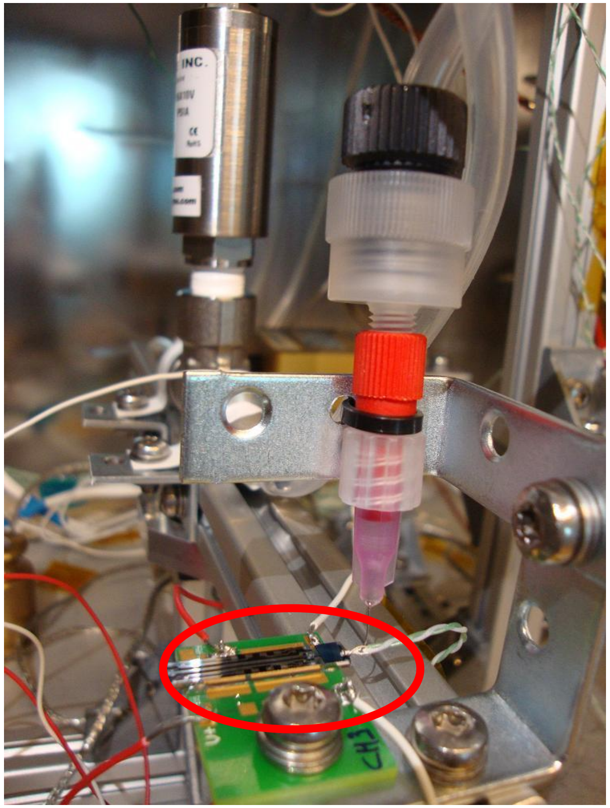
- Extended systems
  - More cold gas generators can be added
  - Very modular and flexible
  - Allow distributed installation within spacecraft

	Nitrogen	Oxygen	Hydrogen
Gas output (normal l/kg)	260	200	1000
Gas release (normal liters/liters gas generator)	290	220	1000
Design output pressure range (MPa)	0.1 - 15	0.1 - 10	0.1 - 20
Gas Purity	>99%	>99%	>95%
Sensitivity to friction and impact	no	no	no

Micro Resistojet Thruster



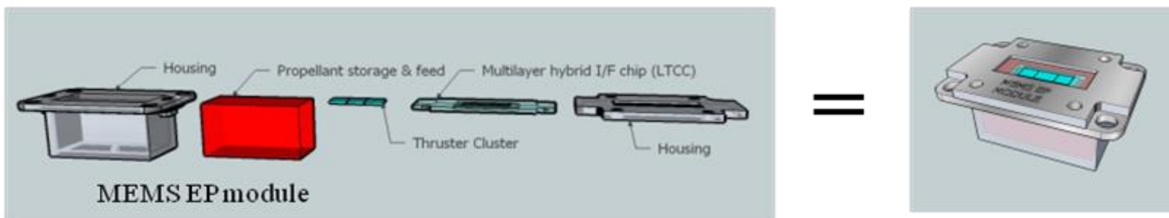


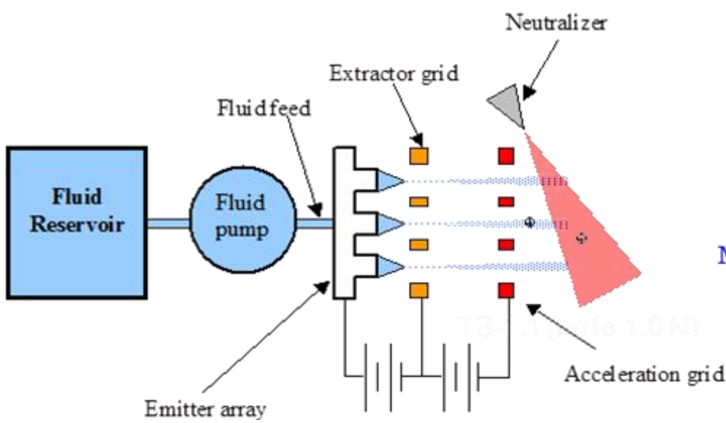


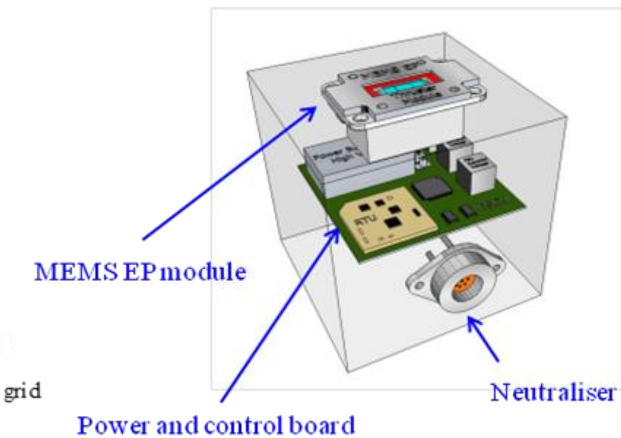
Silicon-based Micro-resistojet System		
Flow channel dimensions	**Value**	**Limitations**
Length	1 cm	No
Height	30-50 μm	No
Width of channel walls	50 μm	Should not be less, in order to have good wafer bonding

Micro Electric Propulsion

- Micro Electric Propulsion of EPFL
  - Uses voltage-driven fluid handling with arrays of individually addressed MEMS capillary emitters with integrated extraction electrodes
  - Baseline propellant being ionic liquid







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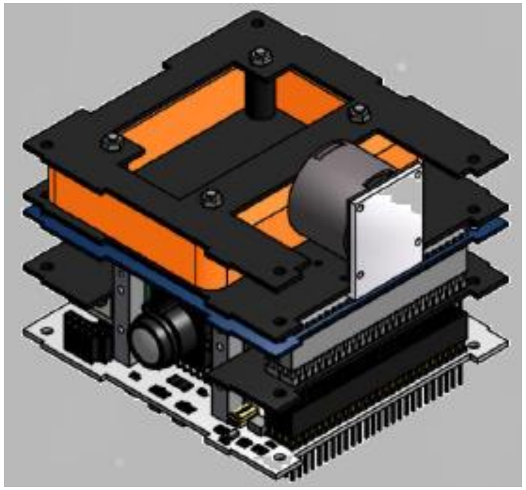
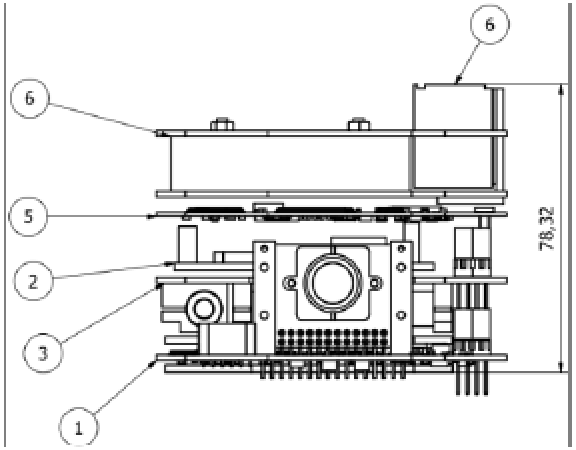
Solutions – System Level

Integrated ADCS Suite

ADCS Unit of Univ. Stellenbosch and Surrey

- A complete OBC and ADCS solution for a momentum biased stabilised satellite
- Configurable to either Main OBC or dedicated ADCS OBC.
- Integrated into a complete module with UART and I2C communications to payload or other satellite subsystems

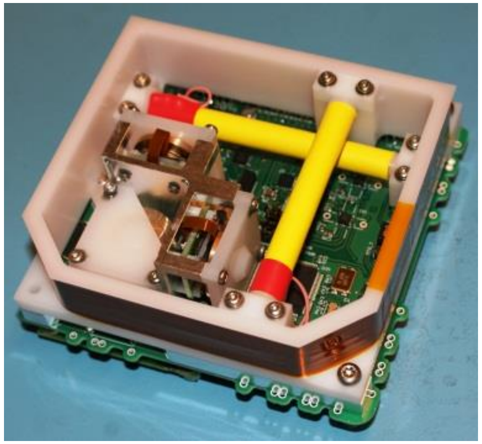




1. CubeSense
2. GPS Receiver
3. CubeControl
4. CubeTorquer coil
5. CubeComputer
6. CubeWheel

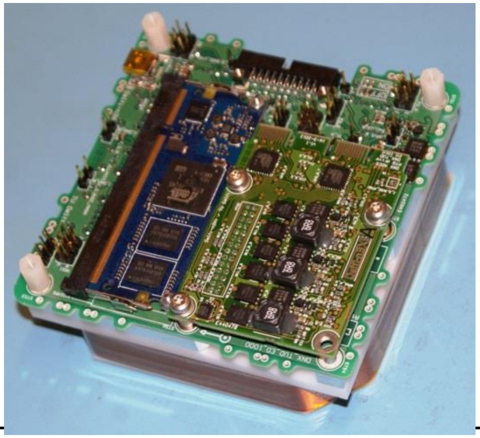
Integrated ADCS Suite

Low-cost ADCS Unit of TU Delft



ADCS Subsystem	
Parameter	Input
Mass	330 g
Power	1600 mW (max)
Volume	90X90X34.6 mm^3
Data	1 Kbits, 2 Hz

3 reaction wheels
3 magnetorquers
2 magnetometers
6 sun sensors
400 MHz ARM9 processor
simple magnetic detumbling
advanced triple-axis control



Underactuated Attitude Control

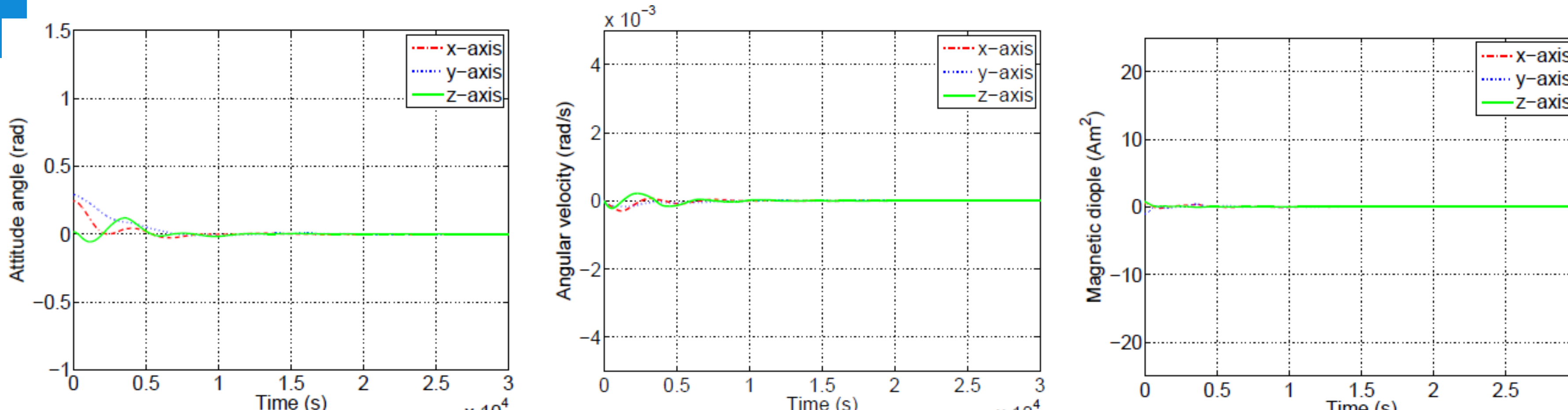
- Lessons learned from actuator failures
  - Hardware redundancies are not always feasible
  - Conventional backup strategy is acceptable but with low accuracy
  - Two actuators are able to provide satisfied control performances under certain constraints

Underactuated Attitude Control (UAC)

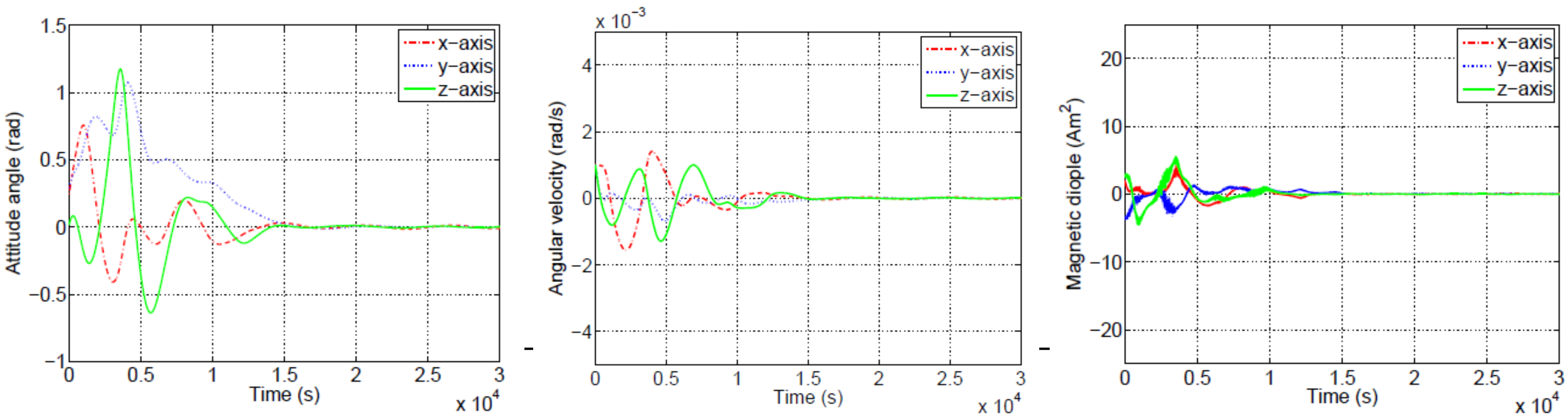
Realizing three-axis stabilization with less than three independent control inputs

Conventional Backup Strategy

Scenario 1: Pointing control with only magnetorquers



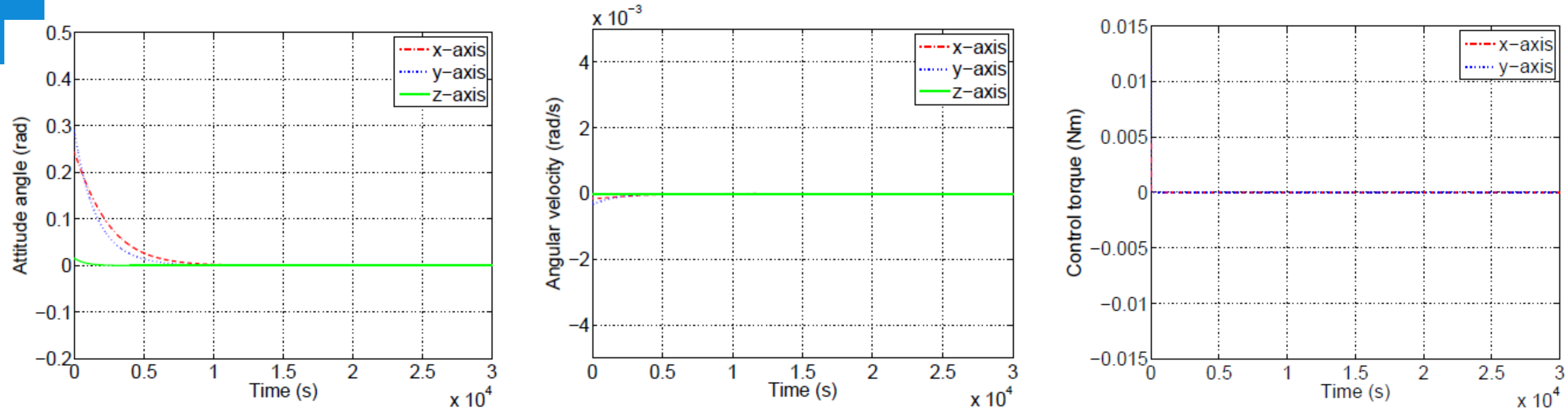
Simulation 1 (ideal situation)



Simulation 2 (non-zero initial angular rate, disturbance, measurement error and remaining magnetic field)

UAC on Small Satellites

Scenario 2: Pointing with 2 RWs (Discontinuous Lyapunov)



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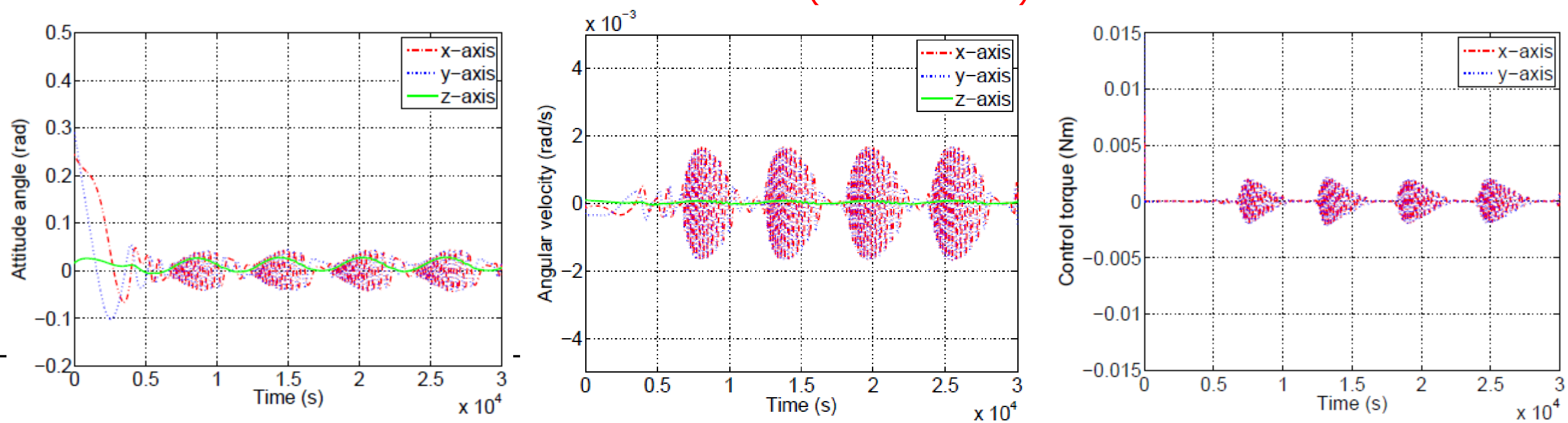
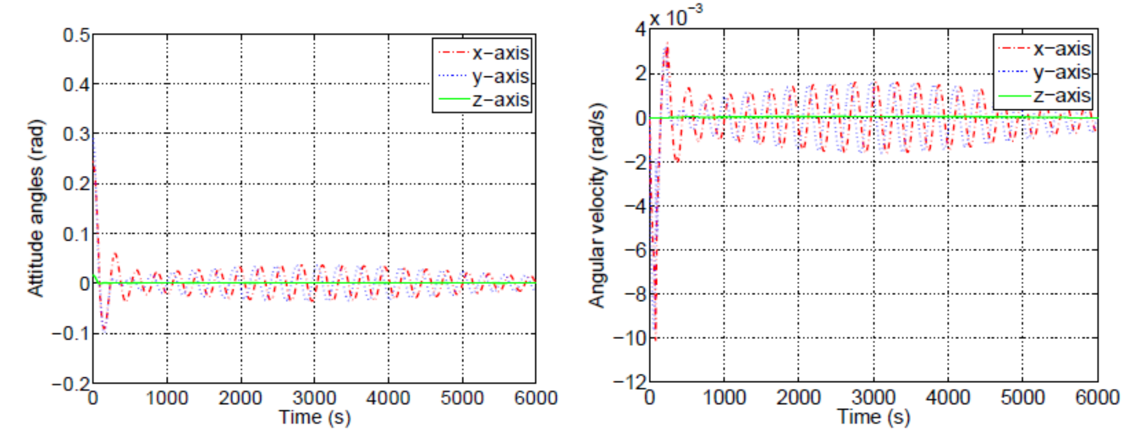


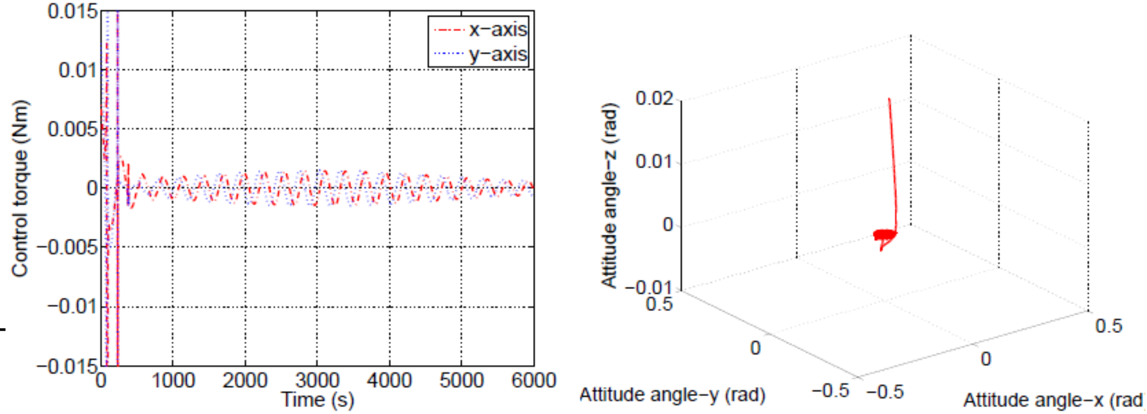
Simulation 2 (non-zero initial angular rate and disturbance)

Improvement of UAC using H∞ Design

Add robustness to the UAC system by satisfying that $HJI(u,V) \le 0$

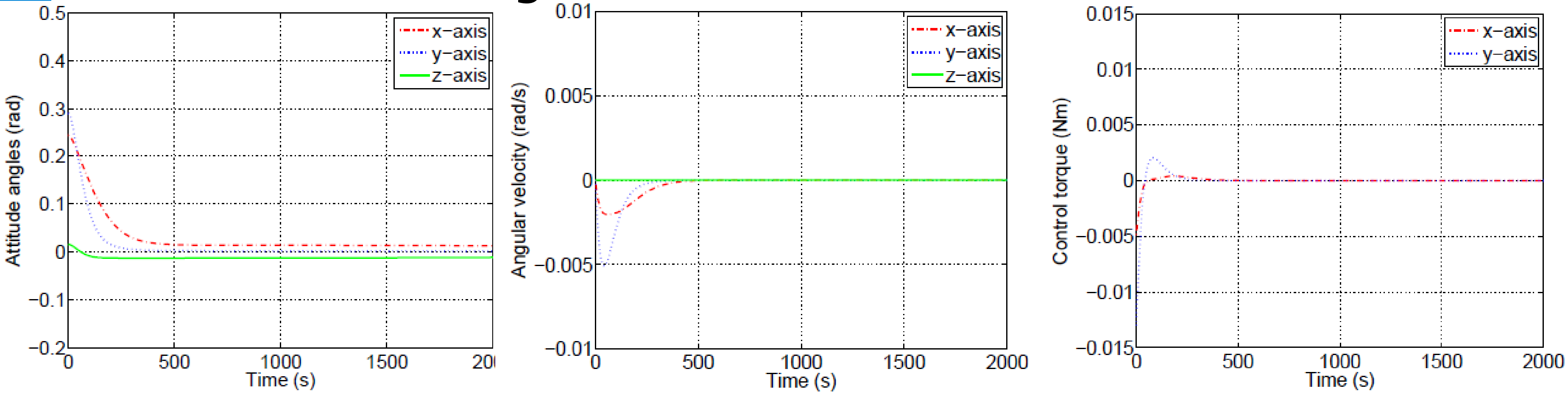


(a) (b)

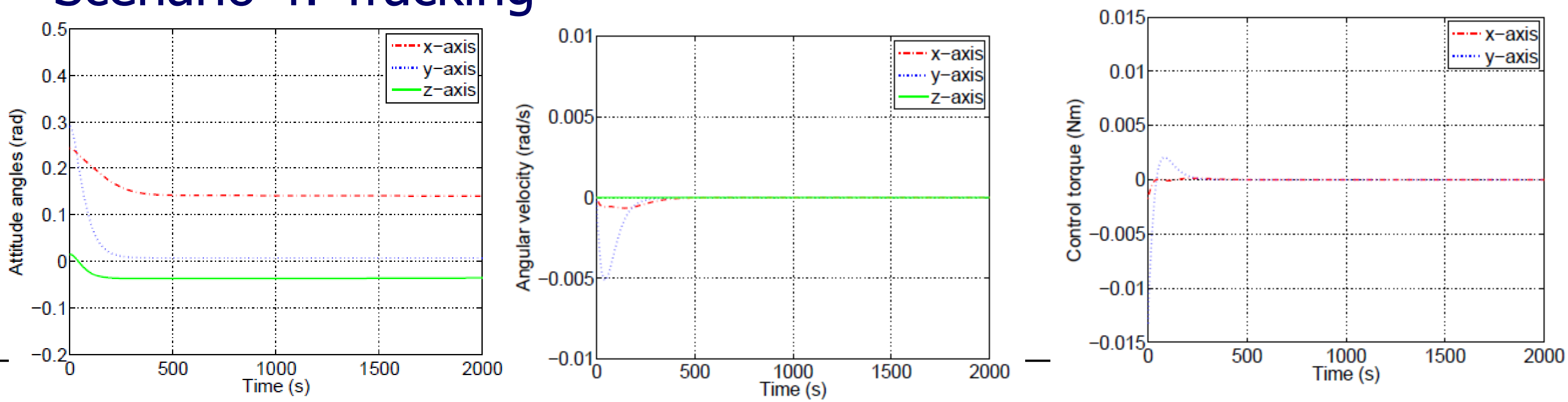


A New Method for UAC using H∞ Design

Scenario 3: Pointing



Scenario 4: Tracking



Review

- What is micro/nano satellite ?
- What are the needs on AOCS of micro/nano satellites ?
- AOCS solutions at component level
- AOCS solutions at system level
- Conclusions