Deutscher Luft- und Raumfahrtkongress 2011
DocumentID: 241329

# ADVANCED PLUG & PLAY SENSORS AND ACTUATORS FOR SMALL SATLLITES

By Stephan ROEMER [1)], Christian RASCHKE[1)] and Stephan STOLTZ[1)]

[1)] *Astro- und Feinwerktechnik Adlershof GmbH, Albert-Einstein-Str.12, 12489 Berlin, Germany*
*Phone:.+49 30 6392 1000, Fax: +49 30 6392 1002, s.roemer@astrofein.com, s.eckert@astrofein.com*

During the last years small satellites (micro, nano and pico satellites) becomes more and more a field for commercial missions. The new requirements, especially high reliability and smartness, results in the design and development of new sensors and actuators especially for long life time missions. This includes not only high performance, but also smartness , means information of the actual potential and performance from the actuators back to the attitude control system, to achieve better and faster performance of the attitude control systems. The paper describes concepts, sensors and actuators for such smart systems.

**Key Words:** attitude control, components, GPS, IMU, reaction wheel

## 1. BACKGROUND

During the last years the requirements in mission life time and performance of attitude control systems for small satellite LEO missions become more and more sophisticated.
This came on the one hand from the evolution of optical payloads, with more and more high ground sampling distance requirements, and on the other hand from the mission requirements. These new mission requirements covers long mission times, and via this high reliability systems, better autonomy of the space segment, and faster reorientation of the systems, which means more targets per pass over a dedicated area.
If the attitude control system (ACS) design takes this into account there are needs for:

- Better control algorithm
- High reliable, high resolution sensors
- Smart and high reliable actuators

## 2. HIGH RELIABILITY APPROACH

Long duration missions from commercial customers requires now 5 to 15 year in orbit life time for the space segment. Combined with the financial risk of commercial (mostly private) investors they can avoid the risk by two strategies:

- Big constellations of low reliable satellites (with replacement)
- Small constellations of high reliable satellites

If we take into account the high launch cost, long mission preparation phases, costs of ground segment, the demands of autonomy and availability of the systems for commercial applications the strategy of using high reliability systems gives the best return per money.
So the attitude control systems for future earth observation missions will have redundancies in hardware and function and also use high reliable sensors and actuators.
Due to the problems in availability of EEE-Parts (old technology, long delivery times and costs and ITAR problems) it is not every time possible to combine the high performance requirements with the using of NASA proofed radiation hard parts.
To solve this problem Astro- und Feinwerktechnik Adlershof GmbH (AFW) with support from ESA, has installed a COTS part procurement program to allow the using of COTS parts without leaving the high reliability approach.
This COTS part procurement program includes the qualification of new EEE-parts for our sensors and actuators. If a new EEE-part should be used in one of the products one complete production lot of the supplier is purchased for the qualification process. 60% of the production lot is used for the part qualification. This includes:

- Non destructive testing like vibration, pyro shock, thermal vacuum testing
- Destructive testing to check the material, connecting technology, bonding, space and line dimensions
- Radiation testing
- Performance testing

If the parts fulfill all requirements the remaining 40% of the parts will be used for the actuators and sensors of our systems. Together with the usage of high reliability parts and the attitude control system design it allows the design and integration of high reliable, autonomous, high performance attitude control systems.

## 3. SYSTEM CONCEPT

To fulfill the requirements, on the one hand of reliability and autonomy and the other hand the high performance in accuracy and agility, the attitude control system concept must be taken behavior of the sensors and actuators into account.
This also includes the fact that classical PI or PID control loops, with their overshoot and undershoot effects are not longer applicable for ACS, especially if high agility is required. This agility is prerequisite for fast rotating of the satellite to allow the small time delays between collecting the data from different swath (up to turning from 30° left from track to 30° right from track in only some seconds).
To fulfill these requirements and to avoid the time delay by over- or undershooting of the system, we use state control loops in our attitude control systems. With its combination of Estimator, Predictor and Controller it can calculate the fastest way for the required new orientation of the satellite, without any loss in accuracy. It must also take into account the time delays, noise and potentials of each sensor and actuator.

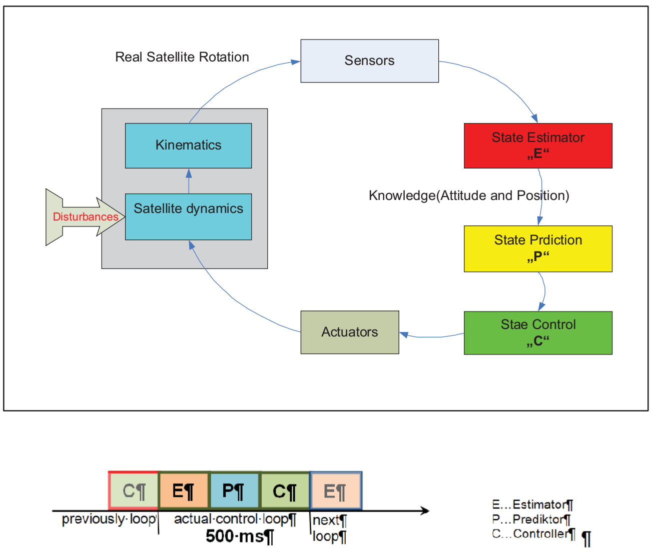


Fig. 1. State control loop

The robustness of the TET AOCS is secured by redundancy of its hardware (H/W) components and a "configuration management system" to handle the redundancy by software (S/W) what provides onboard failure detection and diagnosis. Its robust control loop permits to react against perturbation and component anomaly with sufficient stability margin.
The system for a high performance micro- or nano satellite for high resolution earth observation can be sub-divided into:

- high level software (controller, housekeeper, communication)
- low level software (interface to hardware, i.e. communication protocol)
- hardware/ACS components (sensors and actuators)
- four reaction wheels (tetrahedron configuration)
- two cold redundant magnetic torque systems
- star tracker system including two cold redundant data processing units and two hot redundant camera head units
- two cold redundant magnetic field sensors
- two hot redundant sun sensor systems
- two cold redundant inertial measurement units
- two cold redundant GPS units

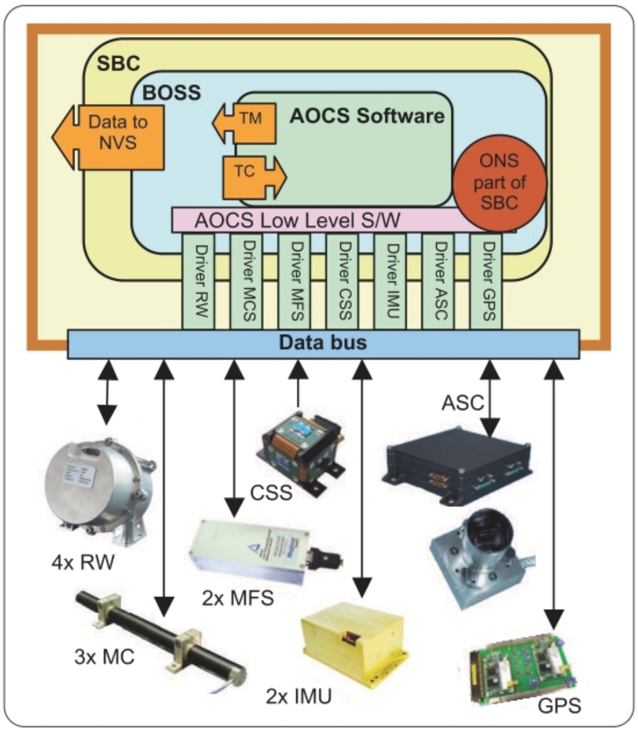


Fig. 2. Software and Hardware (SW/ HW) overview of the TET-1 Attitude and Orientation Control System (AOCS)

## 4. SENSORS

To be integrated into such a system a sensor must fulfill the following requirements:

- high performance
- high reliability
- digital interface
- low power and mass budgets

Low power and mass demands came from the typical small satellite approach and the requirement for digital interfaces came from the needed time delay correction and replace ability of sensors (changing of sensors for different missions).
To combine the requirements of high accuracy and high agility it needs on the one hand sensors with high accuracy but on the other hand with high rotation speed resistance. So this requires typically star sensors and IMUs.

Additional it needs a high precise orbit position and time signal. Typically it is provided by GPS sensor or on-boad navigation software (ONS).
Hereafter some sensors are described as an example.

### 4.1. Magnetic field sensor

Classical magnetic field sensors have an analogue interface and can measure only the earth magnetic field. For good sensors for an ACS a digital interface, for time delay correction and replace ability, is needed. Additional it should be able to measure the sum of earth magnetic field and the magnetic field generated by torquers, if you do not want to lose the sensor information during operating the torquers (e.g. for desaturation of wheels).


Fig. 3. Magnetic Field Sensor

So one possible sensor, which we use in our systems, has the following parameter:

- up to 140000 nT
- Resolution 100pT/LSB
- Noise <50 pT/√Hz
- Linearity 0.025%
- 1.2W, <280g

### 4.2. IMU

Fulfilling the agility requirement, which means fast rotation of the satellite for new attitude acquisition, results in the use of IMUs for detecting the rotation speed with high resolution. Due to the new developments such systems are designed as fiber optical gyros.

Fig. 4. AGS IMU system

Especially due to the ITAR regulations Europe had to develop own systems during the last years. One of them is our AGS with the following behavior:

- Range ±40°/s
- Bias <1°/h
- Noise < 1°/√Hz
- Measurement frequency 200 Hz
- 8 W, 150x100x70 mm

### 4.3. GPS and ONS

To provide the system with actual orbit position data and an accurate time signal we use two systems. On the one side a cold or hot redundant GPS system and on the other hand on-board navigation software.

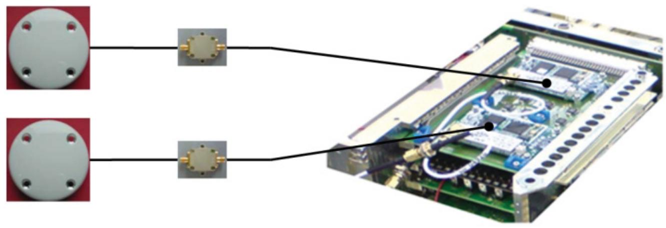

Fig. 5. Redundant GPS system

The GPS system contains of two receivers on a PCB (including latch up protection, interface control …) and two LNA and antennas. The resulting system has the following performance:

- 12 channels
- Code L1 C/A and carrier
- Position accuracy 10 m (3D $1\sigma$)
- Velocity accuracy 0.1 m/s (3D $1\sigma$)
- Time signal accuracy 0.2 µsec
- Warm start TTFF <2 min
- 1.1 W power consumption (for one branch)
- 230 g (for PCB version)
- 160 x 100 x 25 mm (for PCB version)

As functional redundancy to the GPS system a on-board navigation software is used, which combines an orbit propagator with TLEs (which are provided to the system by the Ground station or the GPS system). This backs up the functionality of the GPS with an accuracy in 3D information of <100m.

## 5. ACTUATORS

For typical LEO missions reaction wheels and torquers (for wheel desaturation) are used. Especially the reaction wheels need a high smartness to fulfill the requirements for high accurate but high agile systems. Especially the time delay correction and the obligation of the changing wheel performance capabilities (depending from rotation speed) in question of delivered torques and speeds needs a smart and intelligent wheel.

## 5.1. Reaction wheels

Current analog reaction wheels are “only” electric motors with a flywheel mass. The control of these wheels will be carried out by the satellite’s own processing architecture. Smart reaction wheels relieve the attitude control data processing unit and the satellite’s attitude control engineering team. They are performing tasks which were hitherto part of the attitude control system of satellites, tasks which are related to controlling and monitoring the reaction wheel.

A reaction wheel with a digital interface and a speed or acceleration controller inside is already a kind of smart reaction wheel. AFW expands the term of smart reaction wheels, which are characterized by the following attributes:

- Digital interface
- Monitoring and protective mechanism
- Model based controller

Besides digital interfaces model based controllers are an attribute of AFW’s smart reaction wheels. With model based controllers smart reaction wheels reach higher accuracies and stabilities than standard reaction wheels. They are also operating very accurate in the zero speed area.

Furthermore they are allowing the integration of additional features. These features are for example automatic compensation of displacements, automatic compensation of time delays, presetting of time delays and estimation of acceleration reserve.

Compensation of displacements means that disturbances in wheel operation will be compensated automatically by over or under running the commanded wheel torque or speed. As a consequence in mean the wheel operates as commanded. Because of this behavior the control cycles by the satellites ACS system can be lowered and so calculation power can be saved. Figure 6 illustrates the behavior with a simple example. When commanding a wheel speed jump the wheel takes some time to reach the commanded speed. As a consequence the wheel displacement is rising. The wheel automatically overshoots the commanded speed and the displacement is falling. When the displacement is completely compensated the wheel goes to the commanded speed. In mean the wheel operates over the complete time with the commanded speed.

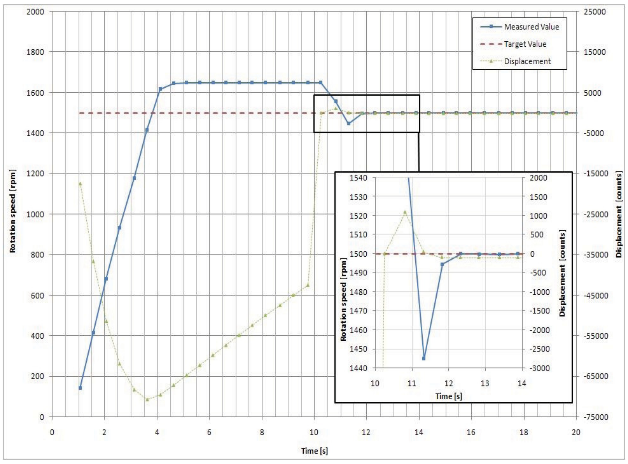


Fig. 6: Wheel speed jump command and automatic compensation of displacement

Estimation of acceleration reserve means that the wheel is estimating its physical parameters (like friction, applied voltage etc.) and predicts its maximum physical possible acceleration. The attitude control system can take this value into account when commanding torques. The figure below illustrates the acceleration predicted by the wheel and the actual reached maximum acceleration.

A further feature is the automatic compensation of time delays. If commands can’t be performed immediately by the wheel when being received, the reception is time stamped and the delay between command reception and performing will be compensated by over shooting the wheel torque or speed.

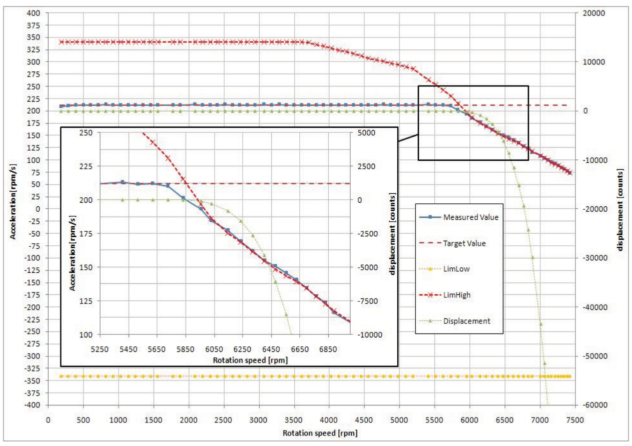


Fig. 7: Prediction of acceleration reserve

All these mentioned features making smart reaction wheels ideal torquers with a high accuracy and stability where the attitude controller don’t have to care about loss torques etc.

Using model based controllers and its related features in reaction wheels will relieve the attitude controller because he don’t have to care about delays in communication and if the wheel reaches its physical boundaries the attitude controller always gets an

information about the limitations resulting from operation in the physical boundaries.
Due to these features smart reaction wheels help to relieve the attitude control team during development and operation of a satellite and as well the attitude controller because both don't have to care about several things (like time delays, loss torques, physical boundaries etc.) that hitherto have to been taken into account by the attitude control system. Consequently development times and costs can be reduced
Typically such reaction wheels for high reliability systems are used in tetrahedron configuration for redundancy.

Fig. 8. Tetrahedron configuration of RW1

Due to the miniaturization of mechanics and electronics such reaction wheels can be offered by AFW for satellites between 400 kg (RW250) and 1 kg (RW 1), which covers the whole range of small satellites.

## 6. ACTUAL USE OF SUCH SYSTEMS

In the actual state of the art satellites such system will be used for micro (<200 kg) and bigger nano satellites (20 to 50 kg). Typical attitude control systems for satellites between 60 and 200 kg allow a pointing knowledge of 10 arcsec, which is primary defined by the accuracy of the available star sensors.
Although there are the actuators for building such systems for small nano and pico satellites there is still a lack of high accurate and smart sensors for such small satellites.
It will be the challenge for the development teams for the next decade. If we can solve these sensor problems, new applications for the smallest satellites will be applicable.

## 7. CONCLUSION

By combining new miniaturization technologies, digital interfaces, time delay correction and model based controllers inside the actuators it is possible to fulfill the new requirements of high performance earth observation missions, and other missions with high accuracy and high agility requirements.
There is still a lack of small but accurate sensors, but they can be developed during the next decade, if also the new reliability requirements of ongoing missions are respected.
The development of a Plug & Play satellite requires standardized and smart components. One step to support this is the application of sensors and especially smart actuators with digital interfaces.

## 8. REFERENCES


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