Three-Axis Disturbance-Free Attitude Control Experiment Platform : FACE

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The Facility for Attitude Control Experiments (FACE) has been implemented at the Institute of Space Systems of German Aerospace Center (DLR) in Bremen, Germany. The facility's objective is testing and verification of the Attitude Determination and Control System (ADCS) under the realistic environment in low Earth orbit. Regarding the evolving ADCS software and hardware, a complete end-to-end verification of ADCS significantly contributes to the mission success. FACE consists of a hemispherical air-bearing with satellite component platform, preliminary solar simulator, and magnetic field simulator. Besides, the implemented automatic center of mass (CoM) calibration software adjusts the CoM of the whole platform and, thus, it can perform minimal friction motions in 3 axes as if in orbit. Furthermore, the platform provides multi-output power distribution system and WLAN command interface. Thus a self-sustaining satellite is arranged on the platform which can be subjected to various tests. A hardware-in-the-loop test using flight components can be performed simply by mounting the desired sensor or actuator onto the platform. In particular, FACE is now prepared for the system verification of DLR's CompactSatellite program. We introduce the real-time test bench with specific devices, their performances, and future extensions in progress.

Key Words : Attitude Determination and Control, Hardware-in-the-loop, Small Satellites, Air-Bearing Table

Nomenclature

$\boldsymbol{h}$: Angular momentum vector, [Nms]
$\boldsymbol{I}$: Moment of inertia tensor, [kgm^2]
$\boldsymbol{\omega}$: angular velocity vector, [rad/s]
$\boldsymbol{T}$: External torque, [Nm]

subscripts
B : Platform including structure
RW : Reaction wheel

superscripts
i : Measurement in inertial frame
b : Measurement in body fixed frame

1. Introduction

The objectives of the Attitude Determination and Control System (ADCS) are to develop a system which can achieve the attitude requirements of the mission and to verify its functionality. The highest level of maturity and reliability of the system are required to minimize the risk of mission failure. However, it is a big challenge to satisfy all the requirements. This is usually referred as Technology Readiness Level (TRL) and it is required to be as high as possible. In order to achieve the highest TRL on-ground, Software-in-the-loop (SIL) and Hardware-in-the-loop (HIL) simulations have been studied and established.

These SIL/HIL strategies are almost essential for verification and validation of the ADCS system today. However, especially related to ADCS, the gravitational force is the major obstacle in simulating the realistic dynamics of a satellite on-ground. The way to circumvent this bottleneck is the pseudo torque-free platform using air-bearing.

The Facility for Attitude Control Experiments (FACE) has been implemented at the Institute of Space Systems of German Aerospace Center (DLR) in Bremen, Germany. One of the objectives is testing and verification of the ADCS under the realistic conditions, and it allows a complete end-to-end verification with desired system configuration of software and hardware.

FACE consists of an air-bearing table with satellite component platform and space environment simulators. The implemented automatic center of mass (CoM) calibration software adjusts the CoM of the whole platform in a very accurate way and, thus, the platform can perform minimal friction motions in 3 axes as if in orbit.

Looking into papers, different types of test facilities can be found ranging from simple single-axis rotation table to sophisticated three-axis air-bearing facilities[1–4)]. A decent overview of the attitude control experiment facilities has been provided by Schwartz et al.[5)] including the history of the air-bearing platform. Bernstein et al.[1)] has developed an spherical air-bearing platform with a steel shaft passing through the sphere. It has an advantage in the range of maneuver angle but, on the other hand, the mass distribution and the resulting moment of inertia are different from the conventional box-shape satellite.

The unique advantage of the FACE is the environmental simulators in addition to the pseudo free floating air-bearing platform. The desired environmental influence of Earth's magnetic field and/or the solar illumination can be employed for specific objective of the experiment.

Besides, there are several extensions set as milestones in our outlook, namely star recognition camera, single gimbaled control momentum gyro (SCMG), structural vibration mechanism, and extended HIL network. These extensions enhance the activity in research and development of the state-of-the-art control concepts. The details of our outlook are described in the later section.

The next section introduces the specification of the FACE facility. The target of the FACE is small satellites (in Europe sense), which means from 100 to 200 [kg] in mass. The facility provides an ideal opportunity for system validation and verification.

The system verification procedure can start with individual model-in-the-loop (MIL) simulation, integrated into the SIL, and finalized with the HIL simulations. The HIL stage verifies the actual hardware with real-time ADCS under the artificial orbit environment and the pseudo disturbance-free motion of the platform. FACE is now prepared for the early stage of system verification and testings for DLR's CompactSatellite program.

2. Introduction of FACE

The facility is based on the heritages from the experiment platform built for TET-1 satellite in DLR Berlin$^{6)}$. Further implementations have been made for the sake of expanding the capability of the facility.

The main task of FACE is to simulate the attitude dynamics of the satellite. This means that the attitude control subsystem including control algorithms can be tested and verified in the loop with the flight hardware.

The major components configure FACE are the host PC, on-board components, satellite platform on the air-bearing, preliminary solar simulator and magnetic field simulator. 3 pairs of Helmholtz coil setup generate a realistic magnetic environment while canceling out the local magnetic field. Additionally, there is a preliminary solar simulator using a high pressure lamp installed in FACE in order to introduce the Sun-related constraints in the experiment.

Fig.1 shows the system overview including the control interface for the whole facility. During the experiment, compressed air is supplied to the platform to perform a smooth motion on the air-bearing. The real-time interface is developed and is controlled from the host PC with Matlab/Simulink coder. It translates the Simulink model into the real-time operating system compatible code, which will be uploaded to the On-Board Computer (OBC).

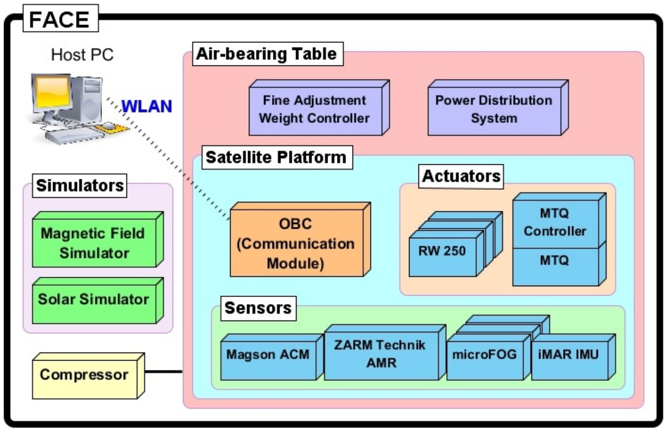

Fig 1. System overview of FACE.

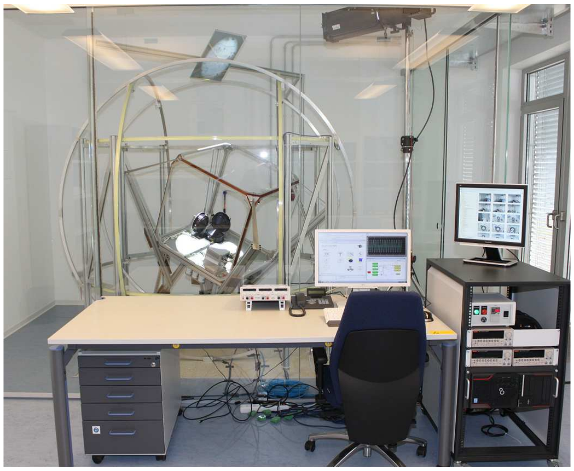

Fig 2. FACE laboratory.

In addition, the platform provides multiple output power distribution system and Wireless LAN (WLAN) command interface. Thus a self-sustaining satellite is arranged on the platform which can be subjected to various experiments. The HIL test using flight components can be performed simply by mounting the desired sensor or actuator onto the satellite platform.

2.1. Platform with environment simulators

The actual setup of FACE is shown in Fig.2. The air-bearing platform, preliminary solar simulator, and magnetic field simulator are supplied from Astro- und Feinwerktechnik Adlershof GmbH in Belrin. Air-bearing table allows smooth rotational motions of no limit around Yaw and ±20 [deg] in pitch and roll, see Table 1.

As mentioned in the introduction, several air-bearing facilities have been developed in government institutes and universities. Air-bearings offer the wide range of experiment in terms of attitude control techniques: pointing, tracking, and performing system identification.

Table 1. FACE specifications.

Component	Specifications	
Air-bearing table	Available volume	0.6×0.6×0.6 [m^3]
	Available mass*	180 [kg]
	Pitch & Roll	±20 [deg]
	Yaw	No limit
Battery	Outputs	3.3 - 30 [V]
Magnetic field simulator	Coil radius	2.4 [m]
	Output range	±210 [μT]
Solar simulator	Color temperature	3,200 [K]

* including structure and assembly platform

The FACE air-bearing platform has dedicated CoM calibration software, which adjusts the CoM of the whole platform in a very accurate way and, thus, the platform can perform minimal friction motions in 3 axes as if in orbit. In addition, the power distribution system based on the re-chargeable battery unit provides the regulated voltage outputs ranging from 3.3 to 30 [V] and available power is greater than 400 [Wh]. The specifications of the facility are given in Table 1.

The magnetic field simulator consists of three pairs of Helmholtz coils for homogeneous field generation and each coil has about 2.4 [m] diameter. The output magnetic field strength is ± 210 [μT] for each pair with 1% accuracy. The realistic magnetic field can be generated with the dedicated control software which is based on the SGP4 orbit model and the IGRF magnetic field model.

Some of the constraints in terms of ADCS are related to Sun, e.g. solar panel and optical sensor orientations with respect to the Sun direction. Therefore, FACE has a preliminary solar simulator with a high pressure lamp spotlight fixed on a tripod.

The spotlight has an aperture and a lens to adjust the beam angle and focus length. The biggest constraint is that the direction of the light with respect to the pivot point is fixed and thus available lighting conditions are limited within the operating range of the air-bearing. However, illumination can be supplied from the top through the mirror or directly from the side (see Fig.2), therefore it can be applied for wide range of mission scenarios.

2.2. Available components on-board

There are several components on the platform which are already functional. An industrial embedded computer CMA 157886 cpuModules, by RTD Embedded Technologies Inc., is used as OBC, which supplies the required hardware and software interfaces between the components.

OBC is composed of several modules, in particular respective modules of CPU, Firewire, WLAN, power supply, Controller Area Network (CAN), and serial communication. The serial communication module offers 8 configurable serial ports, which can be configured to the conventional standard EIA/TIA RS232/RS422/RS485 with jumper settings. The OBC runs QNX, a real-time operating system, and transmits the telemetry data via WLAN to the host PC.

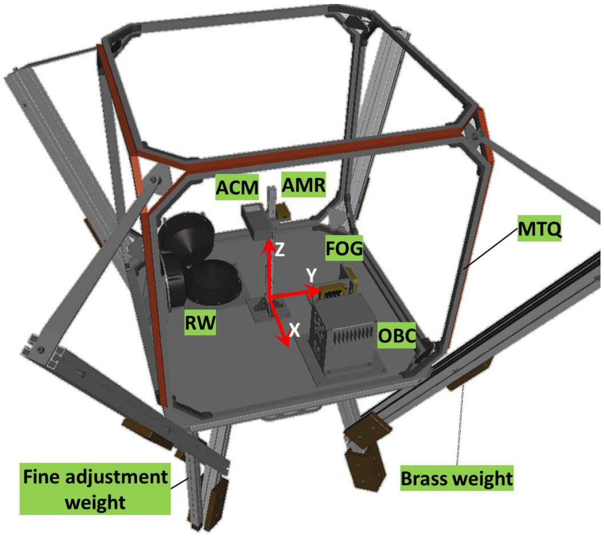

Fig 3. Satellite platform layout and body axes.

Besides the OBC, μFORS-6U Fiber Optical Gyros (FOGs) by Northrop Grumman LITEF GmbH, Attitude Control Magnetometer (ACM) by Magson GmbH, RW-250-1 Reaction Wheels (RWs) by Astro-und Feinwerktechnik Adlershof GmbH, Anisotropic Magneto Resistance (AMR) magnetometer by ZARM Technik, and Magnetic Torquers (MTQs) are integrated on the platform. FOGs, RWs, and MTQs are aligned in each of the body frame axis, see Table 2,3 and Fig.3 for details.

In addition to these components, an Inertial Measurement Unit (IMU) by iMAR GmbH is also available on the platform. The IMU offers a full redundant measurement of the angle and angular rates when used with FOGs and, additionally, accelerometer measurements as well. It has a big advantage that the Euler rotation angles can be directly supplied as an output. On the other hand, its mass and resource requirements are the major issues on the trade off. The configuration of the components including sensors can be arbitrary designed as long as the power resource allows.

The assembly platform has build-in Magnetic Torquers (MTQs) in the box-shape structure. The MTQs are not strong enough to perform the quick attitude maneuver but designed for desaturating the RWs, see Table 3. Combining with the outer Helmholtz coil setups, the desaturation procedure can be performed. This would proceed one further step for the realistic system verifications including RW desaturation procedures and emergency attitude control mode using MTQs.

Table 2. On-board sensors.

Sensor	Size	Mass	Range	Noise	Remarks
FOG	88 x 65 x 21 [mm^3]	150 [g]	±1000 [deg/s]	$\leq$0.15 [deg/$\sqrt{h}$]*	$\leq$6 [deg/h] drift (1σ)
ACM	138 x 55 x 39 [mm^3]	250 [g]	±180 [μT]	<100 [pT/$\sqrt{Hz}$]	±0.05 [%] linearity
AMR	56 x 36 x 17 [mm^3]	55 [g]	$\geq$ ±250 [μT]	<1 [%]	< ±0.1 [%] linearity
IMU	128 x 128 x 104 [mm^3]	2100 [g]	±450 [deg/s]	0.1 [deg/$\sqrt{h}$]*	0.75 [deg/h] drift (1σ)

* Random walk

Table 3. On-board actuators.

Actuator	Size	Performance	Remarks
RW	197 x 197 x 92 [mm^3]	0.1 [Nm] / 4 [Nms]	7000 [rpm] Max., MoI : 5.5x10^{-3} [kgm^2]
MTQ	800 x 800 [mm^2]	6 [Am^2]	platform frame build-in, RW desaturation

3. Implementation

In the first place, the CoM has to be adjusted very well to the pivot point of the air-bearing for simulating the attitude dynamics of a free floating satellite. This is due to the fact that the platform can only rotate around the pivot point of the air-bearing. The displacement between the CoM and pivot point induces an undesired torque that hinder the precise simulation of the dynamics. Besides, it also leads some other negative influences, e.g. RW saturations and errors in the moment of inertia estimation.

The automatic CoM adjustment application has been developed based on the one-dimensional equilibrium condition. The software interface for the stepper motor has been developed, which controls the position of a small adjustment weight (100 [g]) for the precise CoM adjustment of the whole platform. These masses are assembled parallel to each of the body fixed axis[6)].

The CoM is adjusted with the two fold procedure. First, the adjustable brass weight on the platform is used to roughly change the CoM close to the pivot point. Then, the automated CoM calibration runs to precisely place the CoM at the pivot point by moving the adjustment weight. Every component assembly affects the position of CoM and thus, the CoM calibration is required before every experiment if any change has been made on the platform.

By tilting the platform, the torque due to the misalignment of the CoM from pivot point is induced. While compensating the misalignment torque by RWs, the CoM is adjusted by moving the adjustment masses until the torque is below the threshold. Then it proceeds by taking different orientations sequentially to acquire the acceptable CoM position and its error[7)]. For the current setup, the misalignment of the CoM is in the order of few hundreds of micro-meters in each axis.

After achieving the CoM adjustment ready for the attitude experiments, we need to identify the moment of inertia of the platform for each test configuration including its structure.

The developed moment of inertia estimation method is based on the conservation of angular momentum[7)]. This can be assumed since the precise CoM adjustment has been made to simulate the desired disturbance free motion of the platform. The angular momentum of a rigid body with reaction wheels is generally expressed[8)] as,

$$\boldsymbol{h}^i = I_B \boldsymbol{\omega}_B^i + I_{RW} \boldsymbol{\omega}_{RW}^b \tag{1}$$

Note that the moment of inertia tensor I_B in this equation includes that of the RWs. The basic attitude dynamics relates the time derivative of the angular momentum vector to the applied torque. Assuming the angular momentum of the assembly platform is conserved, the torque induced by the RW has the same magnitude with the disturbance torque, but in the opposite direction. Thus, general relation can be expressed as,

$$I_B \frac{d\boldsymbol{\omega}_B^i}{dt} = \boldsymbol{T} - I_{RW} \frac{d\boldsymbol{\omega}_{RW}^b}{dt} - \boldsymbol{\omega}_B^i \times \boldsymbol{h}^i \tag{2}$$

Since we could assume the free floating condition, $\boldsymbol{T} = 0$, we have,

$$I_B \frac{d\boldsymbol{\omega}_B^i}{dt} + I_{RW} \frac{d\boldsymbol{\omega}_{RW}^b}{dt} + \boldsymbol{\omega}_B^i \times (I_B \boldsymbol{\omega}_B^i + I_{RW} \boldsymbol{\omega}_{RW}^b) = 0 \tag{3}$$

All quantities in Eq.(3) are known except for the overall moment of inertia I_B. The angular acceleration is calculated from numerical derivative of the measurement of the FOG and RW is used to apply the chosen reaction torque to the platform. The moment of inertia of the flywheel is provided from the product supplier, and the angular velocity of the flywheel can be obtained as a part of the housekeeping data of the device.

By automating the measurement and attitude estimation process on-board, the three dimensional moment of inertia including the product of inertias are estimated. The automation of the estimation procedure is required from the point of the repeatability. This is because the estimation process has to be carried out for each experiment setup (component and layout).

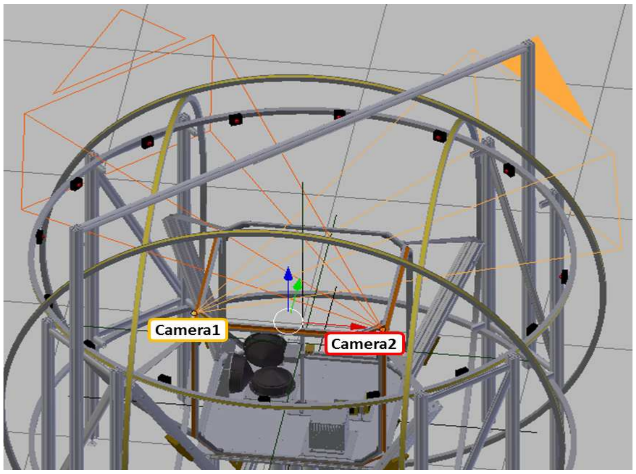

Fig 4. Camera positions and their field of view.

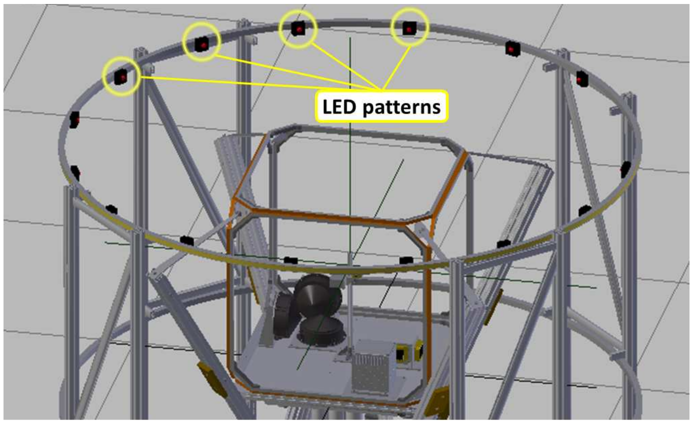

Fig 5. LED pattern layout concept (some components are removed for convenience).

At the same time, the automation is implemented in a way that it guarantees also the safety constraints of the air-bearing, e.g. undesired input errors and mechanical operating range.

The estimation proceeds with angular measurement by approaching different attitudes successively as quickly as possible while drastically changing all body fixed angular rates. The implementation of this procedure requires a guidance that plans ahead and estimates the maximal possible maneuver in order to reach the target attitude within the safety constraints.

The measurement data obtained from the automated procedure is used to calculate the moment of inertia of the whole assembly. For each time step of the measurement data, the derivatives of the FOG measurements were calculated as the average of the change in the time series.

These measurement data were smoothed using a sliding average over 0.2 [sec]. This is because the RWs communicates with a frequency of 8 Hz, unlike the FOGs with 100 Hz. The filtering removes any outliers from the sensor signals that are caused by the discrete sampling rate, leading to smoother numerical derivatives of the each data set.

The estimated moment of inertia of the platform is given in Eq.(4). In general, the moment of inertia tensor has a symmetric matrix of 3 × 3 with six independent components. Nevertheless, the diagonal moment of inertia tensor is obtained from three eigenvalues calculated from these six components. In the attitude experiments, the obtained moment of inertia will be supplied to the attitude control block in order to achieve an optimal control.

$$I_B = \begin{bmatrix} 33.69 & 0 & 0 \\ 0 & 33.04 & 0 \\ 0 & 0 & 30.45 \end{bmatrix} \tag{4}$$

However, the moment of inertia estimation methods are required to be updated since the accuracy of the estimate is still unknown[7)]. According to the layout of the assembled components on the platform, configuration of the brass weights and adjustment weights need to be modified for different experiment configurations. There are several candidates of the estimation procedure can be found in the relevant works[2,9–11)]. It is also possible to find an optimal control method that can compensate the error in moment of inertia estimation.

4. Extensions

On top of the described facilities, further extensions are now being implemented in FACE, namely star recognition camera, structural vibration mechanism, experimental SCMG, and extended HIL simulation network.

- *Star recognition camera* : Star recognition camera will consist of one pair of orthogonally fixed cameras with artificial LED star patterns. Figures 4 and 5 show the 3D drawing of camera positions with their field of view and LED pattern layout concept, respectively.

LED alignment patterns have been investigated and we reached to the configuration of 24 patterns with 7 LEDs in each. These patterns will be fixed on one of the coils of magnetic field simulator, see Fig.5.

The processing algorithm is similar to the star tracker. The extension has two folds procedure, one is to make the catalog of these star patterns and the other is to calculate the inertial attitude direction from the measurement.

The star pattern recognition algorithm process the captured images of the star fields, assigns to them a mathematical description of the patterns, and finds the direction to each imaged star. The centroid of the artificial stars in the CCD must be found first. Then, by some coordinate transformations, the inertial directions of these patterns can be mapped in the pseudo inertial frame fixed on the Helmholtz setup.

This extension provides the pseudo inertial attitude, which can be used to eliminate the gyro drifts. By using this extension, the platform can also offer higher precision inertial pointing scenarios such as space telescope.

- *Single gimbaled control momentum gyro* : For the improvement of the maneuverability of the platform, an experimental single gimbaled CMG assembly is also under its implementation. This has more emphasis on the educational aspect to build up the knowledge on the large angle slew maneuvers. FACE would offer further opportunities for Earth observation and imaging missions with this implementation.
- *Structural vibration mechanism* : This extension has main prospect on research and development of the control methods for mechanical vibrations. The attitude oscillations induced by flexible structures, like solar panels and booms, are the target to be controlled. This implementation is still in progress and is expected to contribute achieving an accurate and stable attitude maneuvers. We are also interested in the optimization scheme for the attitude oscillation control method employing the SCMG.
- *Extended HIL simulation network* : Furthermore, there is a concept of an extended HIL network connecting different laboratories in DLR. There are several laboratories for specific projects inside the DLR and by connecting these facilities as a node in the simulation loop would broaden the horizons of the use of the facility. We can already foresee some development milestones; for example, the MIL or SIL from the early stage of project and, eventually, the dynamic HIL test combining the platform with orbit propagator and/or additional instruments from other facilities. The SIL and HIL tests under the realistic environment in FACE significantly contribute to the system verification and refinement of the system.

FACE can be used as an ideal tool to acquire and visualize a concrete understanding in the attitude dynamics of spacecraft for students and young engineers. From the practical point of view, the platform can also be utilized to investigate the component layout including harness.

5. Summary

We presented the details of an experimental facility FACE implemented at DLR Bremen. FACE is for the development, validation, and testing of a satellite attitude determination and control systems. This facility is an ideal tool for visualizing the realistic attitude motion of a satellite and will be indispensable for attitude control research conducted at DLR. The experimental spacecraft simulator incorporates a wide variety of sensor/actuator configurations. The whole system is modeled accurately so as to reproduce the actual system to a high degree of fidelity.

We summarize our paper in threefold;

- ▷ FACE has been integrated containing, minimal disturbance torque air-bearing table, environmental simulator, and several conventional satellite components
- ▷ The integrated ADCS can be tested in realistic LEO environment including the flight hardware and actual control algorithms
- ▷ The on-going extensions of the facility are expected to broaden the opportunities for education, research, and development

Besides the current capabilities, several extensions are in progress, which would provide further expansion in terms of applicable mission scenarios and fields of research. FACE would significantly contribute also in educating students and young engineers by visualizing the pseudo-free floating dynamics as if in orbit.

FACE is now prepared for the system verification of DLR's CompactSatellite program. Most of the installed components will be directly used for its early stages of the system verification and refinement iterations.

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