A small satellite of the University Stuttgart - a demonstrator for new techniques

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Abstract – The *Flying Laptop* is a micro-satellite currently under development by the Institute of Space Systems. Several promising technologies will be implemented. A high agile attitude control system with a pointing knowledge better than 7 arcseconds, operating in a target pointing mode for image acquisition is necessary to achieve the planned scientific measurements. For communication a high speed Ka-band link using a travelling wave tube will be utilized. The on-board computer consists of a reconfigurable, redundant and self-controlling field programmable gate array with high computational power. In addition to the new technologies for the satellite bus a capable functional verification environment is under development applicable to the *Flying Laptop*.

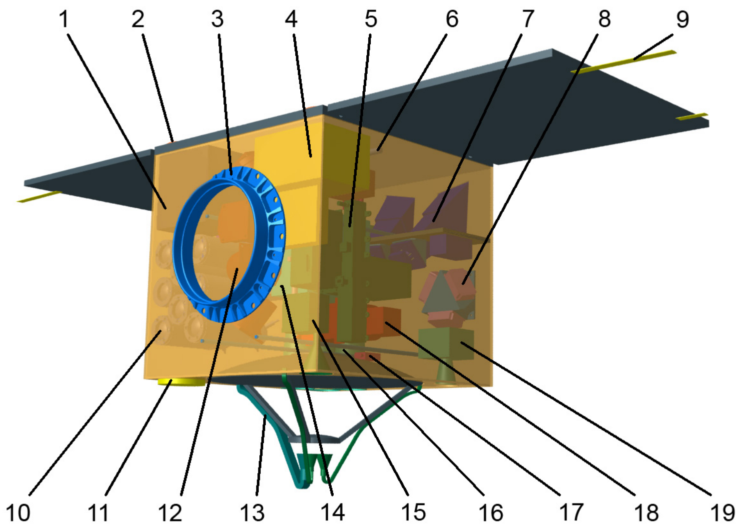
Keywords: Micro-satellite, Flying Laptop, Technology-demonstration, FPGA, Institute of Space Systems, Stuttgart

1. INTRODUCTION

The *Flying Laptop* will be the first micro-satellite of the University of Stuttgart, Small Satellite Program. The primary mission objective is to demonstrate and qualify new small-satellite technologies for the future projects. As a secondary objective, multiple scientific earth observation experiments are planned. The satellite body has a cubical shape with an edge length of 60 cm and a mass of less than 100 kg. Figure 1 shows the general design of the satellite including its components. The launch as a piggyback payload is planned for the end of 2006. A polar, sun-synchronous, low earth orbit below 1000 km is being pursued. As scientific payload the satellite is equipped with a 3-camera system (VIS/NIR), a thermal infrared (TIR) camera and a Ka-band communication system. The last two are intended to make dual use of a cassegrain mirror system.

2. SATELLITE BUS

The mechanical structure of the *Flying Laptop* is divided into the service module, the core module and the payload module as shown in Figure 2. The launch adapter is attached to the back plane of the service module. All modules are made of aluminium due to its high heat conduction properties. In order to ensure the alignment of the cameras (VIS/NIR) to each other and to the star cameras, all components are attached to an optical bench made of carbon-fiber-reinforced plastic (CFRP) for thermal stability. The focus distance of the TIR camera and the Ka-band antenna is also influenced by thermal extension. Hence, the primary mirror and the retaining structure of the secondary mirror will also be produced from the temperature stable CFRP. For the TIR the primary mirror demands a medium surface roughness of approx. 0.8 µm.



1 Power Control & Distribution Unit
2 GPS antennas
3 Launch adapter
4 COM electronics
5 KA-band TWT
6 Magnetic torquers
7 Star Trackers
8 Rate Sensors
9 COM Antennas (LG)
10 Batteries
11 COM Antennas (HG)
12 Reaction Wheels
13 Feed horns
14 On-board Computer
15 Ka-band feed horn (LG)
16 VIS/NIR Camera System
17 Magnetometer
18 TIR camera
19 Panorama camera

Figure 1. Design of the *Flying Laptop*

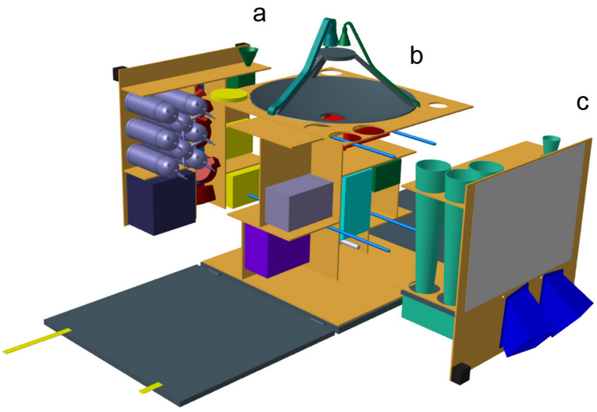


Figure 2. Modular design of the *Flying Laptop*, a) Payload Module, b) Core Module, c) Service Module

2.1 Mechanical structure and thermal system

The mechanical structure of the *Flying Laptop* is divided into the service module, the core module and the payload module as shown in Figure 2. This design allows a convenient access to the internal components and ensures simultaneous integration of the modules. All segments are made of aluminium due to its high heat conduction properties. Furthermore the three modules are held together by rods, which go through the whole structure and are fixed by locknuts. The launch adapter is attached to the back plane of the service module.

To achieve a thermal stable alignment of the camera optical axes with regard to the star tracker it was decided to mount all the camera sensors to a single optical bench made of carbon-fibre-reinforced plastic (CFRP) sandwiches with aluminium honeycomb. The composite of the optical bench is chosen in a way to prevent high thermal extension in normal direction of the camera axis.

As a further constraint, the thermal extension effects on the focus distance of the TIR camera and the Ka-band antenna shall be negligible. Therefore, the 500 mm primary mirror of the dual Cassegrain System and the retaining structure of the secondary mirror will be produced from CFRP. The primary mirror must meet the required mould and a medium surface roughness of approx. 0.8 µm due to the wave length of the TIR camera. The roughness will be reached by metallization of the surface. A specific configuration of the payload cameras is described in [1].

For power generation one fixed and two deployable solar panels are installed on the *Flying Laptop*. The structure of the solar panels is also made from CFRP sandwiches which consist here of aluminium folded core structures as interlayer as developed for aeroplane structures by the Institute of Aircraft Construction of the University of Stuttgart. The folded aluminium core structure affords no enclosed air and furthermore a simple reinforcement possibility in critical areas of the panels, e.g. frame joints.

The thermal system of the *Flying Laptop* is intended to be passive by using the dissipated heat of the internal components. The heat is emitted by a radiator attached to the payload module. Quartz over Silver (OSR) or Second Surface Mirror (SSM) are intended to be used as radiator material because of its low ratio (about 0.1 [2]) of solar absorptivity against its infrared emissivity.

Heat dissipation in the diverse operation modes is significantly different. In safe mode a heat of about 20 W is generated by the components, for the period of normal operation a heat of about 60 W is dissipated and a maximum heat of about 250 W for 20 minutes is exhausted during broadband communication. This peak load is affected by the Ka-band traveling wave tube. These high differences in the dissipated heats demand a heat accumulator to keep the satellite in the required temperature range of -5°C to 20°C. The thermal system of the *Flying Laptop* will be designed to reach the minimal temperature in the safe mode, a middle temperature in the charging mode, and maximum temperature during the broadband communication mode by storing excess heat in the capacitive heat accumulator. The Ka-band traveling wave tube will only be used once in an orbit, as the batteries have to be recharged after a Ka-band communication.

Heat pipes are additionally taken into consideration to achieve a high thermal conductivity towards the radiator. Furthermore the *Flying Laptop* is covered by multi layer insulation (MLI) in order to protect the satellite from high temperature changes in its orbit.

2.2 High accurate and agile attitude control system

The *Flying Laptop* is a 3-axis stabilized micro-satellite. The attitude control system (ACS) needs to provide an absolute pointing knowledge of 7.4 arcseconds or one pixel, and to avoid color fringes a relative pointing knowledge of 2.5 arcseconds (1/3 of the pixel size) for consecutive images and agile maneuvering capabilities in accordance with the planned earth observation instruments. This is a big challenge for a micro-satellite and can only be achieved by a thorough control concept and high performance sensors/actuators.

Figure 1 shows the actuators and sensors of the ACS. The ACS connections to the OBC are illustrated in Figure 3. The actuators consist of reaction wheels and magnetic torquers. Four reaction wheels are aligned in a tetrahedron configuration and each has an angular momentum capacity of 0.12 Nms. Three magnetic torquers (torque rods) dump the momentum accumulated by the reaction wheels. The moment of inertia in the x, y and z axis of the satellite is estimated to be approx. 4 kgm^2.

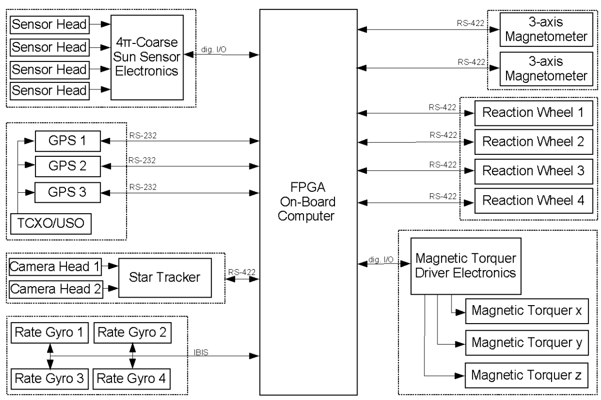


Figure 3: ACS block diagram

The satellite motion is monitored by five different types of sensors: 3-axis magnetometers, a coarse sun sensors unit, rate sensors, an autonomous star tracker and GPS receivers. The new Zarm AMR-magnetometer uses a magneto-resistive sensor and provides a digital interface. For the measurement of the angular velocity, four fiber optical rate sensors will be used. A star tracker, the micro Advanced Stellar Compass (µASC), from the Technical University of Denmark will provide pointing knowledge within the range of 2 arcseconds. After the satellite is stabilized and rotates with a slew rate of less than 1.2 °/s the star tracker delivers regular high precision attitude updates. To provide full accuracy about all axes and to decrease the probability of blinding during maneuvers, a second camera head unit is mounted on the satellite with its optical axis tilted 22.5° away from the first one. To support accurate target-pointing of the spacecraft during imaging and ground station contacts, the satellite will be equipped with a GPS navigation system. Three Phoenix GPS receivers are provided by DLR/GSOC and are locked to an ultra stable 10 MHz crystal oscillator for an orbit and attitude determination experiment.

For image acquisition three different attitude control modes are defined and shown in Figure 4: inertial-pointing mode, nadir-pointing mode and target-pointing mode. In the target-pointing, also known as spotlight mode, the satellite points to a fixed spot on the surface of the earth during a fly-over. This allows longer integration times for the cameras which is a significant advantage for the scientific measurements. The slew rate for this maneuver is 1 °/s (max.) and follows a non-linear bell-shaped curve over time. This is the most demanding mode of the satellite in terms of control algorithms.

In safe and detumbling mode only the magnetometer, magnetic torquer and one reaction wheel will be active. The spacecraft will rotate twice per orbit around its pitch axis following the Earth magnetic field lines once the Bdot control law is converged.

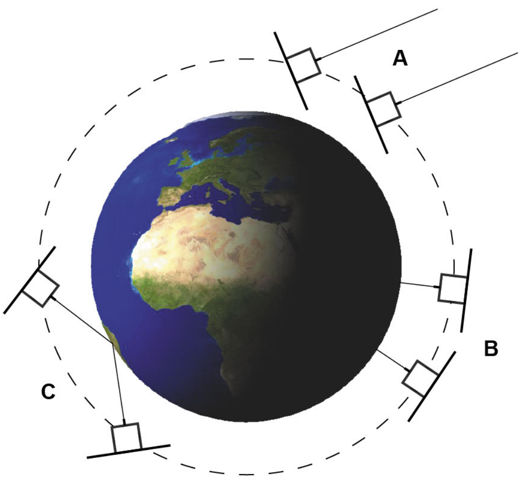


Figure 4. Imaging Modes:
A) Inertial- , B) Nadir- & C) Target-Pointing Mode

2.3 FPGA On-Board Computer System

The *Flying Laptop* will probably be the first micro-satellite using a field programmable gate array (FPGA) as primary on-board computer (OBC). The OBC is based on a Xilinx Vertex-II Pro with approx. 3 million system gates and a clock frequency of 200 MHz. The OBC will further consist of 4 MB of synchronous static RAM for high speed data processing, 2x 128MB DDR RAM and 1 GB Flash. Via a modem, a user programmable EEPROM can be reconfigured from the ground station. In case of failure, the original FPGA configuration is restored from a PROM.

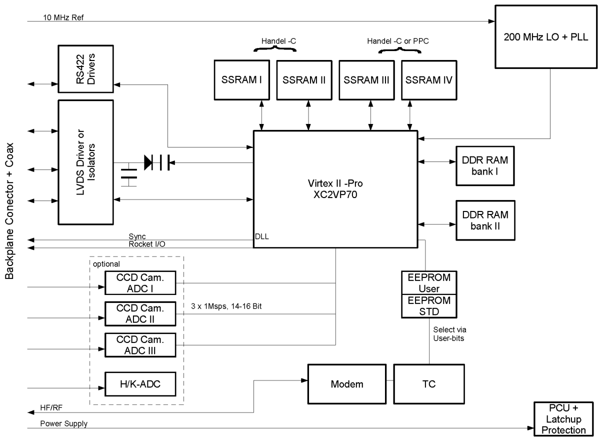


Figure 5: FPGA OBC block diagram

With a software-to-hardware compiler it is possible to directly generate the logical configuration of FPGA gates from a C-like high level language without producing the machine code for a processor. Through this approach massive parallel processing is possible. To make the system fault-tolerant and to address radiation issues, four equal independent nodes will work together. Depending on the state of the system 1-4 nodes will run at the same time and are dynamically switched on or off. A complete start-up of a single node takes only 10 ms. The high flexibility of the on-board computer system will be used to operate the *Flying Laptop* in a so-called *Rent-A-Sat* mode. It is possible to configure the system for customer preferences (i.e. the characteristics of a certain processor can be simulated through the hardware). With this versatility the system is well-suited for OBC software or component firmware validation in space. The OBC system (Figure 5) is currently under development by the Steinbeis Transferzentrum Raumfahrt in cooperation with the Fraunhofer Institute for Computer Architecture and Software Technology.

2.4 Communication System

For telemetry and telecommand VHF, UHF (low gain) and S-band (low and high gain) antennas will be installed on the satellite. Beside S-band communication, VHF and UHF offers the possibility to utilize amateur radio equipment. As payload the *Flying Laptop* will be equipped with a Ka-band traveling wave tube (TWT) amplifier. During a ground station fly-over, the TWT will operate with an RF transmission power of 57 W (170.5 W DC input) which is unique for a micro-satellite. With this subsystem a data rate of 100 Mbit/s is being pursued. The satellite's cassegrain system with its 50 cm primary dish provides the antenna reflector for the Ka-band communication and is also used as the optical system for the thermal infrared camera. Additionally, the Ka-band TWT can also be used as radar emitter. The TWT is the design driver for the NiH_2 battery system to handle the TWT high power requirement for a duration of max. 20 minutes.

3. FUNCTIONAL VERIFICATION APPROACH FOR THE *FLYING LAPTOP*

Setting up a verification environment for reliable system-wide tests is new to micro-satellite projects, but it is one of the enabling technologies for proving the required attitude control system accuracy. In this context a software-based functional verification system reduces the check-out environment complexity and huge costs can be saved.

This model-based verification environment for small satellite applications is under development in close cooperation with EADS Astrium [3] and will be set up in parallel to the *Flying Laptop* development. It is characterized by high real-time capabilities to represent the spacecraft hardware in its exact operational modes and response times. Software models of the spacecraft components will be created successively in adequate detail in order to provide the particular test bench functionality. Latest commercial improvements in hardware and software technology allow the real-time test benches to be set up using standard computers and a Linux operating system kernel which supports real-time performance.

A Software Verification Facility (SVF) is in progress to support the on-board software development process. The schematic structure of the SVF is illustrated in Figure 6. It is used to debug, validate and verify the on-board software and prove the overall system dataflow functionality. In this test bench configuration the real-time simulator (RTS) consists of a real-time spacecraft simulator (S/C SIM), an on-board computer simulator (OBC SIM) and a central control system (CCS) which provides a TM/TC interface, simulator control and debugging interfaces.

The SVF supports real-time or accelerated software simulation of the whole spacecraft system. This is achieved by implementing all spacecraft components by its hardware-specific software models into the spacecraft simulator. The real-time simulations are supported by space environment models, thermal and power models and a spacecraft dynamics module.

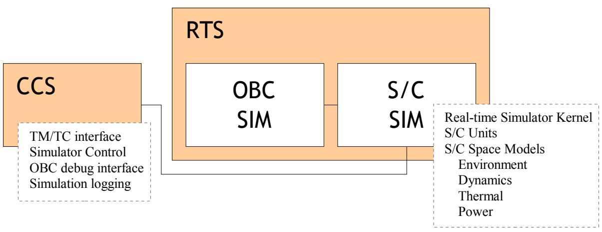


Figure 6. Block diagram of the Software Verification Facility

In the next step a FlatSat test bench with high real-time performance will be arranged as initial hardware check-out environment including no more than the on-board computer as hardware in the loop. It will be set up well before spacecraft integration using test harness to maintain single component up to system-wide check-out procedures. All software models of the hardware components, especially those of the attitude control system (ACS) or the Power Supply System (PSS), will be re-used in this environment to verify correct operation. A powerful computer based on the standard i686 processor architecture and operated on a real-time Linux derivate forms the backbone of the Real-time Simulator. Multiple PCI-Bus interface cards will be used as interfaces between the flight hardware components and the spacecraft simulator.

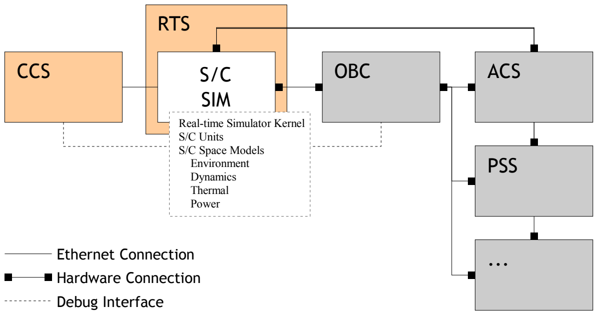


Figure 7. Block diagram of the FlatSat test bench which integrates flight hardware (grey shaded) in the simulation loop

The third test bench is created as an expansion of the FlatSat test bench and integrates additional spacecraft hardware in the simulation loop (refer to Figure 7). Single component check-out tests will be followed by complete mission scenario simulations. Finally the protoflight test bench supports a functional verification test environment throughout the flight hardware qualification process.

4. CONCLUSION

The *Flying Laptop* is a micro-satellite under development by the Institute of Space Systems, University of Stuttgart. High accuracy and agility are the essential characteristics to be fulfilled by the attitude control system. A new on-board FPGA computer system and a high speed Ka-band communication link, are only two of the promising technologies under development for the satellite bus. Furthermore a low-cost but reliable simulation and test environment is under implementation to support system-wide functional verification during the *Flying Laptop* qualification process.

5. REFERENCES

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