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South African Satellite Operations Testbench for Capacity Building in Space Operations Training and Research

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Abstract

More and more countries are operating their own national satellites. In recent years, states like Peru, Angola, Bangladesh and Qatar have launched their very first satellite missions. Many of these states aim for multiple socio-economic benefits: the mission tasks typically cover disaster management, agricultural monitoring, water management, fisheries and national security. With their own ground stations and a mission control system, such satellites can be fully controlled by the corresponding national institution after launch. A problem that emerging space nations often face is that of knowledge transfer to their respective local industry and academia, especially in the area of onboard computers, onboard software and operations. In 2016, the University of Stuttgart and the University of Cape Town (UCT) decided to strengthen and deepen the cooperation in research and education in the field of space sciences and technologies between both institutions. This partnership, supported by additional industrial sponsors Cobham Gaisler, Sweden and Terma B.V Netherlands, and Airbus provided UCT with a fully representative satellite simulation, a digital twin of the "Flying Laptop" mission. This comprises the simulator, the flight software and a real mission control system – namely the Satellite Control and Operation System CCS5. The CCS5 runs together with the spacecraft simulation software on a single high-performance workstation. The third application is the flight software development environment. Multiple monitors allow users to simultaneously display the different parts of the simulation as it is running: The Airbus simulator SimTG (Simulator Third Generation) itself, the hardware emulator for the onboard software called TSIM, and a visualization of the satellite in orbit. This equipment enables now satellite software development and operator training at University of Cape Town. For UCT, this is a significant step in academic excellence, R&D and innovation and capacity building in the field of space sciences and technology. The training in Cape Town will be performed by students who gained experience at Stuttgart University and further insights from Airbus Defence and Space in Friedrichshafen. This ensures that the personnel in Cape Town will be fully trained in the operation of the system. In addition, phone support from experienced Airbus engineers is available. At the time of writing this abstract, the system is being established. The team at UCT will simulate a flight scenario which covers vegetation monitoring using optical payload instruments and a detailed explanation on how to model a satellite and its subsystems as well as the effects of the simulator on local capacity growth. This will be an impactful demonstration of South African academic competence in mission operations and spacecraft modelling.

Keywords: Training and Knowledge Transfer, Simulation and Operations, Educational application of Space Operation

Acronyms/Abbreviations

ACS – Attitude control system
CCS5 – Satellite Control and Operation System CCS5
CCSDS – Consultative Committee for Space Data Systems
ESA – European Space Agency
PC – Personal Computer
PUS – Packet Utilization Standard
SANSA – South African National Space Agency
S/C – Spacecraft
SimTG – Simulator 3rd Generation (Airbus satellite simulation toolkit)

1 Introduction

In recent years many emerging space agencies of various countries around the world are formed. States like Egypt, Angola, Nigeria, Qatar, Brazil have launched or about to launch their first satellites. Many of these nations invest in space technology to help improve their socio-economic benefits. They use satellites to help with disaster management, national security, vegetation monitoring (agricultural land, impact of urban spatial development and grasslands).

The problem these states are confronting is that the knowledge of space technology is not being transferred to their local industry and academia. Most of these states use existing mature space nations to build and control the operations of their satellites with limited knowledge transferred back to local engineers or scientists.

If emerging space nations have their own antenna and ground station, they can operate their own satellites after launch. Usually emerging space nations are limited by financial constraints of their budgets to develop launch sites, own launch capabilities and other main ground infrastructure to propel satellites into space, etc. But they are able to transfer knowledge on the following particular systems of a satellite: the onboard computer, onboard software and operations of a satellite.

In particular to South Africa as an emerging space nation, UCT has partnered with the University of Stuttgart to establish a satellite simulation testbench of the "Flying Laptop" mission, and with their industrial partner Airbus Defence and Space. The "Flying Laptop" is a 120kg microsatellite with dimensions of 60x70x80 cm^3. This academic satellite has been developed in cooperation with Airbus Defence and Space and was developed following a paradigm to initially simulate the satellite and after design has been consolidated (including flight software and operations concept), to subsequently replace simulated equipment by real flight hardware in the loop – until the satellite is complete. This approach is described in detail in [3].

1.1 The "Flying Laptop" Satellite

The primary objectives of the "Flying Laptop" is to perform Earth observations using the multispectral cameras and maritime tracking of ships using the automated identification system (AIS). It was developed at the University of Stuttgart in collaboration with Airbus Defence and Space. The satellite was developed and built by PhD, Masters and senior undergraduate students, all providing contributions to the satellite or research related to the satellite. It was launched in 2017 and is operational since then.

Figure 1: The "Flying Laptop" Satellite fully assembled, 2017 before Shipment to Launch © IRS, Uni. Stuttgart

The "Flying Laptop" satellite consists of the following subsystems:
- Payload
- ACS
- Telemetry, tracking and command
- Data handling
- Thermal control system
- Power supply system
- Mechanisms (deployable solar panels)

The spacecraft (S/C) is operated applying industrial command and control standards such as the CCSDS telecommunication channel and the ESA packet utilization standard. Its computer is based on a radiation hard LEON3FT chip and internally is based on a SpaceWire architecture using the remote memory access protocol (RMAP) for SpaceWire protocols [1][2]. The "Flying Laptop" has six different control modes: detumbling mode, safe mode, idle mode, inertial pointing mode, nadir pointing mode and target pointing mode.

The detumbling mode is to slow the rate of rotation of the satellite. The safe mode is used when there is a failure on the satellite. The idle mode is used when the payload is not in operation, but the satellite is doing routine operations. The inertial, nadir and target pointing modes are used when the payload is in operation.

1.2 The UCT Simulator Testbench

The SimTG simulator from Airbus Defence and Space models the S/C, space environment and the S/C dynamics. It runs on a PC with Linux operating system and in more advanced hybrid configurations, it is able to run the spacecraft simulation in real time. The satellite and its subsystems are simulated by software models of each hardware component. The modelling is performed in C++ language with a user interface that resembles MATLAB. Telecommand and Telemetry packet definitions about the simulated models are stored in the Mission Information Base (MIB) of the connected Mission Control System (MCS) which itself is based on CCS5 from Terma A.S., Netherlands.

The simulator infrastructure consists of:

- The Flight Software development environment including Flight Software in source code.
- The mission control system CCS5 which is a standard for ESA and its industry partners.
- The real-time S/C simulator with the satellite equipment models in source code.
- 3D visualization based on the Celestia software with diverse satellite geometry models.

Figure 3 provides an overview of the main machine interface for each of the elements. In the current sponsored setup, all functions run on a single PC for cost reasons.
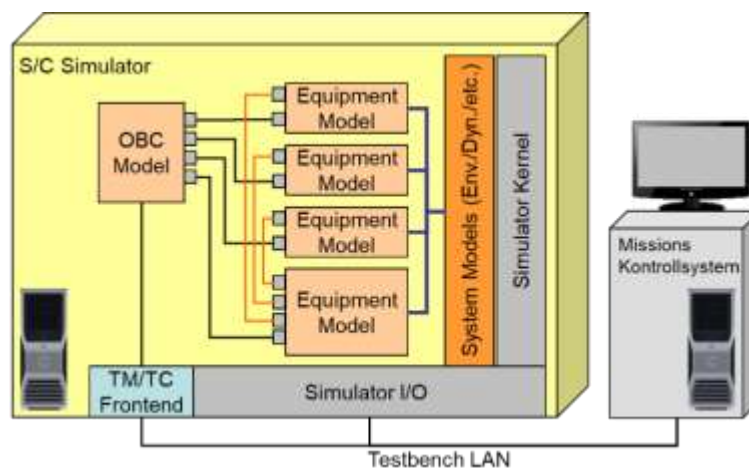

Figure 2: Simulator Testbench with fully simulated Onboard Computer © J. Eickhoff, from [3].

Such a fully simulated "digital twin" of a satellite can be used for flight software development and for development of satellite operations and failure management concepts. The simulator in this testbench simulates the onboard data handling, a simplified radio-transmission subsystem (without RF chain), power management and a simplified thermal control subsystem. The payloads are rudimentary models only, since the simulator shall later be modified to model camera equipment from local South African suppliers (in example SCS Space).

A flight operation can be commanded on the simulator from launch phase, to in-orbit operation to End-of-Life disposal. This paper will demonstrate commanding of the first passover scenario to the simulated "Flying Laptop" and will demonstrate capacity building in satellite operations and use of Flight Software and a professional MCS. The selected flight scenario targets for vegetation monitoring which is South Africa's main objectives of satellite research.

2 Vegetation Monitoring in South Africa

The South African Mission Advisory Committee's (EO - MAC) main objectives are to use remote sensing for vegetation monitoring in South Africa. This objective has been transferred to South Africa's next Earth observation satellite, the EO-SAT1. Other South African satellites that have contributed to vegetation monitoring in the past are SUN-SAT1 and SumbandilaSat.

Vegetation properties such as quality, species, biomass etc. can be achieved by using multispectral and hyperspectral sensors. Vegetation includes crop, forest and rangeland monitoring. The current biomes in South Africa are: grassland, savanna, succulent Karoo, Noma Karoo, forest, fynbos, desert and thicket [4].

Figure 3: Simulator Testbench Screenshots © UCT, IRS Uni Stuttgart and Airbus.

South Africa's main goal for vegetation monitoring is to do vegetation species discrimination, standing vegetation, biomass estimation, vegetation health or quality and vegetation cover mapping [4]. In addition, monitoring vegetation to cover change which relates to both vegetation quality and species mapping is of interest.

The study of vegetation monitoring allows researchers to see the effects of climate change on areas due to droughts or rainfall, farm animals eating grasslands, farmlands growing and reducing wildlife and the effect of urban development on surrounding grasslands.

South Africa National Space Agency (SANSA) plans to create a national co-ordinated programme to increase remote sensing skills and continue investment in high resolution space-borne imaging systems and advanced image processing capability. With optical camera systems on satellites the size of EO-SAT1 or the "Flying Laptop", vegetation monitoring with substantial resolution and in multiband spectral spread can be achieved.

For the first simulated scenario using the testbench - which was experimentally commanded to the real "Flying Laptop" by the University of Stuttgart - the panoramic camera was used which has a wide field of view and almost natural colour spectrum.

3 Flight Scenarios

The presented flight scenario mimics vegetation monitoring over the Cape Town area using one satellite. The defined operations sequence is the first commanded to the UCT simulator and provides satellite simulation of the flight and the step by step commanding. The same flight passes were then commanded by Kai Leidig at the Institute of Space Systems (IRS), University of Stuttgart, to the real "Flying Laptop" satellite which generated imagery of the Cape Town area.

3.1 Simulated Scenario

The elaborated mission scenario comprised two observations in two consecutive orbits passing approximately over the Cape Peninsula. To analyse realistic ground tracks, the Two-Line Elements (TLEs) of the real "Flying Laptop" were introduced into an orbit analysis tool and the simulation propagated the virtual satellite along the tracks accordingly.

In Figure 4, the 2D ground track of the flight scenario for Cape Town is shown as well as a 3D orbit for when the satellite passes over Cape Town, captures images and then sends the data down when it passes over the IRS ground station.
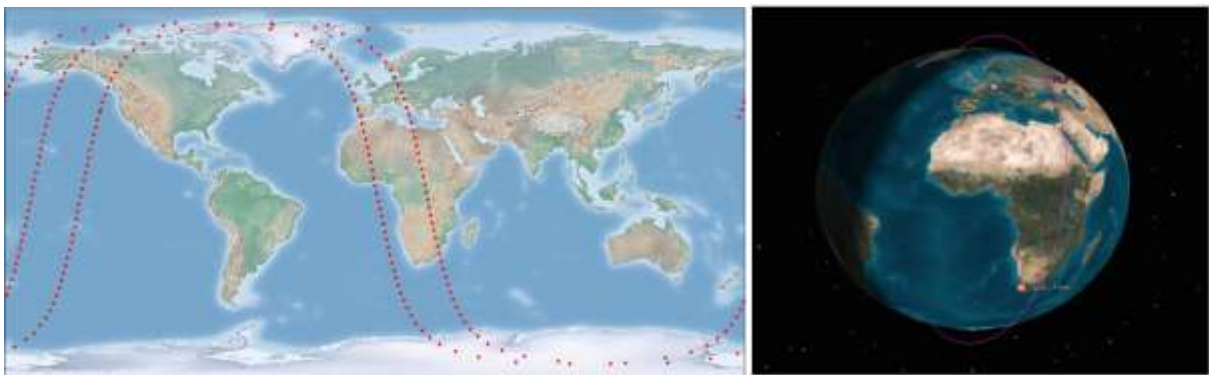

Figure 4: Mission planning in 2D with IRS and target visibilities and sun/eclipse. © Airbus DS

The set up of the pure flight scenario comprises the simulation initialization, loading of flight software, specification of a consistent orbit propagation start condition of the satellite with all its parameters. In addition to that, a simplistic commanding of a virtual vegetation monitoring camera was added to gain a first-hand experience on the topic of payload commanding.

Table 1 shows a breakdown of the mission plan procedure for the satellite during its orbit. The table only covers one of the consecutive paths. The satellite was in idle mode in orbit, before it reached its target point. From the table it can be seen that the satellite first changes from idle (sun-pointing rotating) mode to inertial mode and then next to nadir pointing to get the camera view "down to Earth". Then the satellite is commanded to point to the target (Cape Town), rotating to left looking in the pass leading East of the Cape and right looking in the pass transiting West of the Cape. Since the simulated satellite does not yet have a realistic payload modelling, the level of detail ends at this stage.

Table 1: Procedure outline for Cape Town flight scenario

Step Number	System/Subsystem	State Transition	Satellite Mode	ACS Mode
0	System		Idle	Idle
1	System	Activate nominal operations mode	Idle	Idle
2	Payload	Stand-by mode	Nominal operations	
3	System/ACS/Payload		Nominal operations	Inertial Pointing
4	System/ACS/Payload		Nominal operations	Nadir Pointing
5	System/ACS/Payload		Nominal operations	Target Pointing
6	System/ACS/Payload	Image acquisition mode	Nominal operations	Target Pointing
7	System/ACS/Payload		Nominal operations	Nadir Pointing
8	System/ACS/Payload		Nominal operations	Inertial Pointing
9	System/ACS/Payload	Payload Idle mode		
10	System/ACS	Activate system Idle mode	Idle	Idle
11	Payload	Off mode		
12	System		Idle	Idle

3.2 Scenario Commanded to "Flying Laptop" Satellite

The vegetation flight scenario on the simulator was now commanded to the real "Flying Laptop" satellite by University of Stuttgart. The satellite performed two ascending passes, one from the East and another from the West, with the focal point on the Cape Peninsula. For simplicity of operations, the satellite's panoramic camera was used instead of the multispectral one. Both cameras anyway would not be realistic for a professional vegetation monitoring as e.g. performed by the European Union's Copernicus Sentinel-2 fleet.

The "Flying Laptop" satellite captured 30 images of the Cape Peninsula in both passes. The picture shown was taken during the overpass that occurred on the 18th of February 2020. The pass number 15440 is shown in Figure 5 when the satellite was targeting the Cape Peninsula from the East. Figure 5 shows the field of view and the satellite ground track – both from the IRS mission planning tool. Figure 6 shows the captured image from the satellite of the Cape Peninsula – unfortunately with several reflecting clouds.
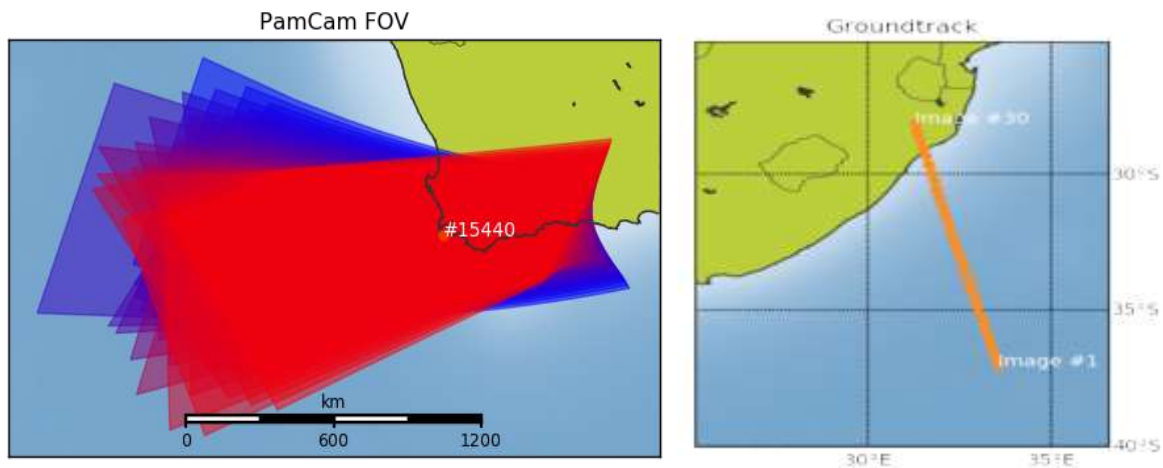

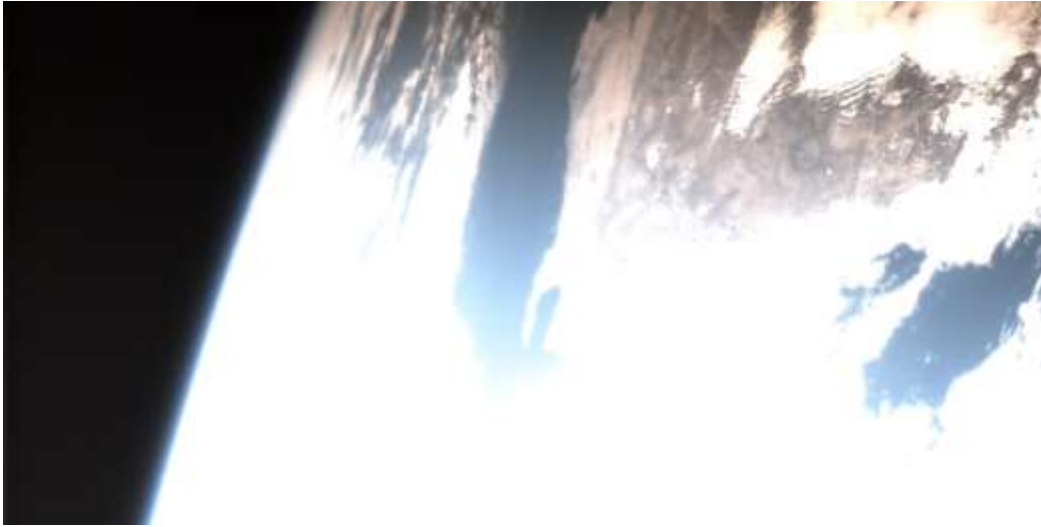*Figure 5: Panoramic Camera Field of View for Passover one and Ground Track*

Figure 6: The Cape Peninsula – © IRS, Uni Stuttgart

The pass number 15442 is shown in Figure 7 when the satellite was targeting the Cape Peninsula from the West. Shown in Figure 7 is the panoramic camera's field of view and satellite ground tracking. Figure 8 shows the captured of the Cape Peninsula and St. Helena Bay – again with a lot of clouds since this was the consecutive orbit 90 minutes later.
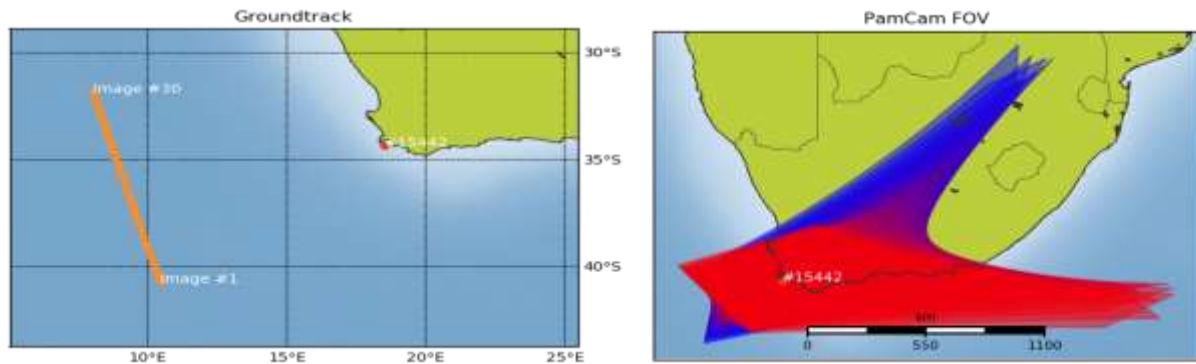

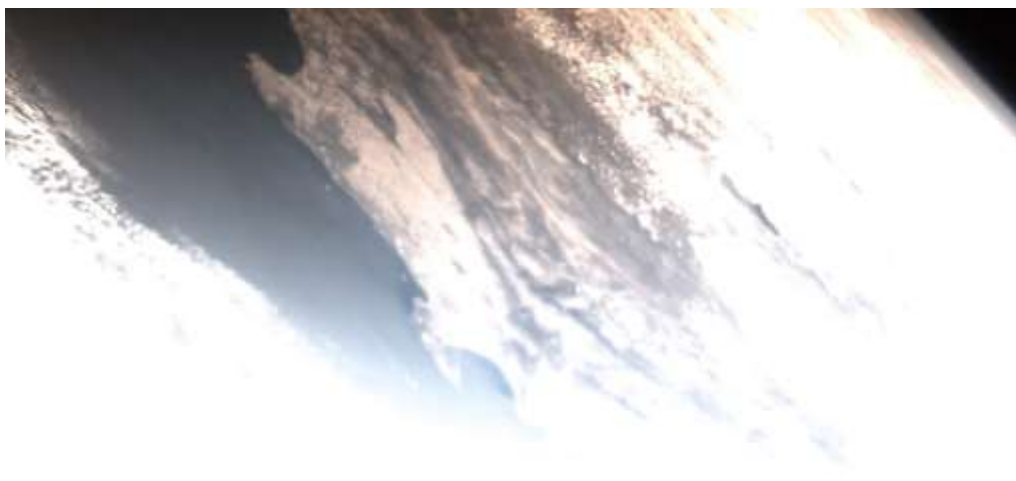*Figure 7: Panoramic Camera Field of View and Satellite Ground Track*

Figure 8: Cape Peninsula and St. Helena Bay – © IRS, Uni Stuttgart

4 Better Coverage with Multi-Satellite Constellation

In Figure 9, there is a good quality image of the Cape Peninsula, achieved through a satellite pass leading directly over the Cape Peninsula and during clear sky conditions. The photo is an older image from the "Flying Laptop" from 2018, taken with the same panoramic camera.

Figure 9: Good quality picture of Cape Peninsula through Nadir looking Passover – © IRS, Uni Stuttgart

To achieve a shorter revisit cycle to reach the target as above in realistic time intervals, often enough, preferably in nadir pointing mode and to track plant growth on weekly basis, usually a fleet of 2-4 or more satellites is useful. This implies the capability to operate a fleet of satellites in constellation or formation. For this purpose, the IRS, University of Stuttgart, has developed the Multi-Mission Operations Toolkit (see [7]). For testing this with realistic scenarios up to four simulated satellite instances of the same type as now available for UCT are being commanded. Figure 10 shows a block diagram of the internals of the toolkit and Figure 11 provides an impression on the user interface.
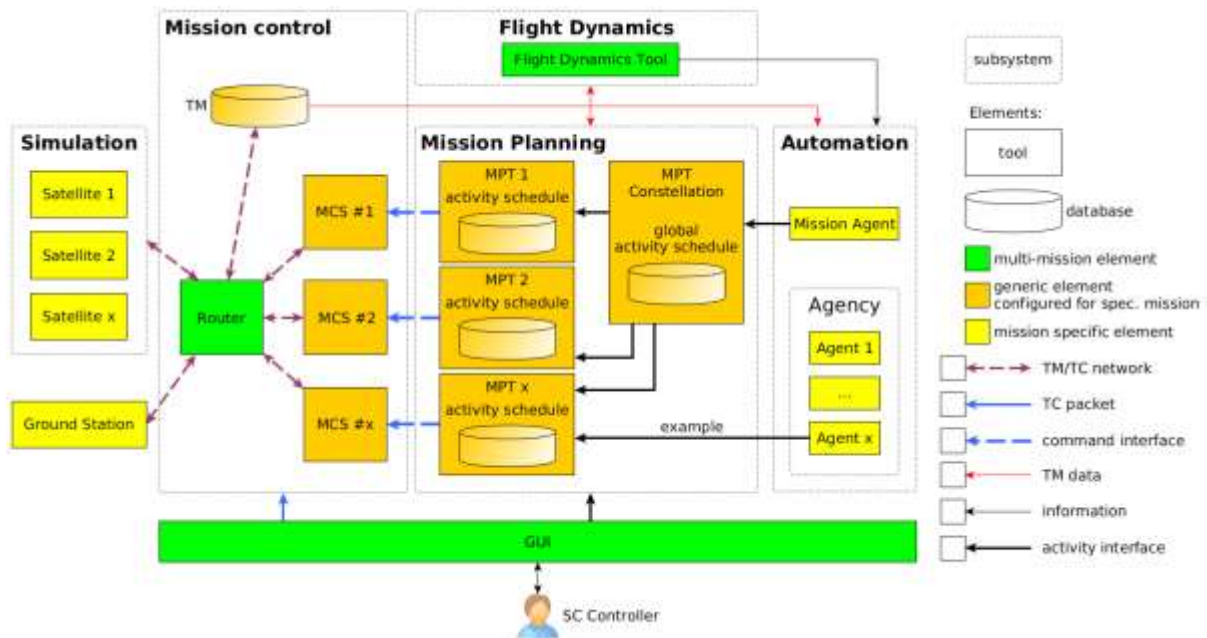

Figure 10: Multi-Mission Operations System Architecture © K. Leidig, IRS, Uni Stuttgart [7]

*Figure 11: Multi-Mission Operations System –
User Interface
© K.Leidig, IRS, Uni Stuttgart [7].*

5 Effects on Local Capacity Growth

5.1 Lectures

During the last years UCT has acquired a number of guest lecturers who contributed significantly to the knowledge in satellite design, onboard computers and onboard software as well as in satellite operations, simulation and verification - see Figure 12.

- The lectures for satellite onboard computers focus on radiation hard and commercial space microprocessors, on data buses, command decoding and telemetry encoding and all main elements that make-up the onboard computers.
- The onboard software lectures focus on the software that runs on onboard computers, payload computers and data processing, satellite memory, the complex AOCS subsystem and also the power control and distribution unit. Students learn about onboard software static and dynamic software architecture.
- The lectures for satellite operations allow students to understand the satellite's operational concept design. This includes the S/C operational phase concept and the satellite authentication concept, to just list a few. Other topics are S/C onboard autonomy, failure recovery operations, mission operations infrastructure and training.
- The satellite simulation lectures teach students simulation-based approaches used in design verification and infrastructures for spacecraft as a well as the different setups of verification infrastructure that can be applied.
- The satellite verification and testing lectures teach students on how to efficiently verify onboard software and hardware equipment for the satellite and how to create a functional test program for the onboard software and environmental test of the hardware.

Figure 12: Students learning about space operations in a classroom © UCT, SpaceLab

The now available simulator testbench extends significantly the possibilities for the students since it allows for hands-on experience in these fields using a virtual satellite with a full featured real onboard software. This can be used for hands-on trainings and workshops. And can be the nucleus for deriving from the existing design a future South African satellite mission. It opens the door for Master and PhD thesis projects in satellite software, design, verification and simulation.

5.2 Spacecraft Modelling

Spacecraft modelling involves modelling all aspects of the spacecraft from the subsystems of the satellite to the communication protocols, power consumption and electrical interfaces between all systems and subsystems.

As students get used to working on the simulator, they learn to model all aspects of a satellite in depth as done in (local) industry. This reduces the gap between local academia and industry and improves the coordination between these two spheres.

Students learn to model and test the satellite subsystems in MATLAB/Simulink and transfer the models from Simulink to the simulator. Important models to simulate on a satellite would be the AOCS, the thermal control and the power control subsystems. All these models and their control algorithms can be verified and tested on the simulator testbench.

5.3 Satellite Operations

Satellite operations involves specific phases throughout the lifetime of a satellite such as:

- The Launch and Early Orbit Phase
- The Commissioning Phase
- The Routine Operations Phase
- And finally the Disposal Phase known as the De-Orbit Phase.

The simulator testbench will help the students as well as South Africa to grow in those four keys areas of satellite operation while allowing students to experience all the phases of satellite operations and train them in the mission operation execution.

The simulator will also provide students with experience being part of a flight control team consisting of: the flight director position, various subsystem specialists like command operator, planner, flight dynamics, ground data systems.

This will contribute to reduce gaps between local industry and local academia. In future students would be well equipped with industry standards, hands-on experience and operational knowledge. The experience gained would be applicable to any spacecraft, especially LEO and GEO missions, which are the most commonly used. For South Africa, LEO spacecraft operation would be most beneficial, to increase remote sensing applications.

The UCT testbench surely will attract South African satellite operations industry.

5.4 Handling a real Satellite Flight Software

Students gain experience in handling the CCS5 generic mission control system. The mission control system allows students to learn how to create command and telemetry definitions as well as synoptic displays for different space missions. It also offers to learn how to monitor and control more than one satellite as satellite operators. This is an invaluable skill that can be utilized in industry and further reduces gaps between academia and industry.

When students leave for industry, they will be able to contribute to the development of own satellite flight software for local entities helping to boost South Africa's impact in the global space market. This will significantly increase the level of knowledge and expertise in commercial companies and governmental organisations. Local partners will have the opportunity for training students to use their satellite flight software allowing more valuable time to be used for development. Great commercial opportunities in cooperation with Airbus Defence and Space are opened up here, since Airbus Defence and Space uses the same flight software architecture in their "Flexible LEO Platform" (FLP2) for small and medium satellites. Industry partners also will be able to write software drivers for their local payload sensor products for the FLP2 platform to offer them to a global community.

5.5 Enabling Space Research

With this testbench based on the FLP technology, software and simulation infrastructure UCT and its South African collaborators become partner of a global community of users. South African institutions like UCT and local industry can partner with other nations already investing in the newer "Flexible LEO Platform" (FLP2) technology from Airbus Defence and Space and with their partners for future missions, like Thailand and potentially later the Philippines as shown in Figure 13.

Figure 13: Partners cooperating on missions based on the "Flexible LEO Platform" (FLP2) © Airbus Defence and Space

The UCT testbench will also allow students to perform more hardware in the loop testing and this will further allow UCT to be a centre for South African satellite development greatly improving South Africa's remote sensing technologies (e.g. cameras, sensors, data processing algorithms). Figure 14 shows the types of applications South Africa could develop for it satellites.

Figure 14: Multi-Mission Operations System Architecture © K. Leidig, IRS, Uni Stuttgart [7]

6 Conclusion

The simulator testbench is the essential step forward to enable UCT and its students to gain practice in the so far lectured technology fields

- Onboard Computers,
- Onboard Software
- Operations Scenarios,
- Simulation and Verification

The simulated satellite with its LEON3 processor and SpaceWire architecture represents latest technology as used by global space players – e.g. at Airbus Defence and Space. With further funding in example from SANSA or local industry the simulator testbench setup at the University of Cape Town has the potential to be upgraded to the Airbus "Flexible LEO Platform" design and could resemble the testbench currently installed at the Chulalongkorn University in Thailand [10]. This testbench brings latest technology hands-on expertise to South Africa.

Acknowledgements

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