CONCURRENT DESIGN FACILITY AT THE SPACE CENTER EPFL

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Introduction

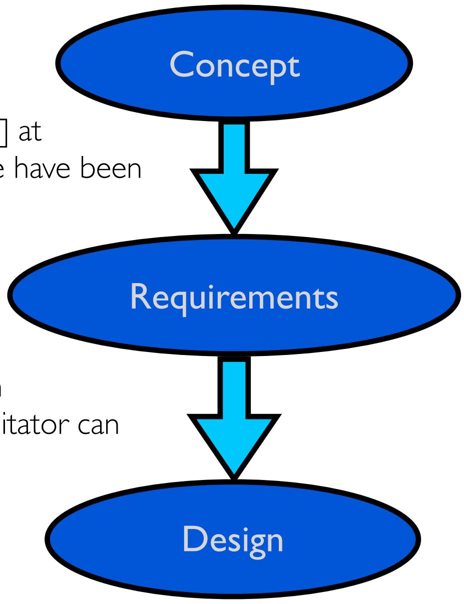
The Space Center EPFL was founded to foster, promote, and federate space technology across education, science and industry at Swiss and international levels. These objectives have been accomplished so far by the development of the SwissCube satellite, the setup of the EPFL concurrent design facility, the creation of a Minor in space technology, the launch of the EPFL space research program in 2006, and a close relationship with industry. Space Center is the leading organization in the SwissCube nano-satellite project. The satellite has been launched in September 2009 and currently operational.

Concurrent design facility (CDF) is an environment where engineers of different specialties come together to perform system engineering study for a project. Key elements for a CDF are team, process, environment (including A/V and software) and knowledge management. Benefits of a CDF for industrial implementation [*Fijneman*, 2010] include faster design of new products, shorter time to market, overall quality improvement, knowledge re-use, fast implementation of trade studies. For the academic environment goals have to be completely different because there is no commercial product delivered at the end and product lines do not exist. This paper will describe the process of setting up a facility in a university and will try to answer a question of where CDF concept can fit into education.

The Space Center CDF facility has been funded as part of of the Fond d'Innovation pour la Formation of EPFL (internal funding). The primary direction for CDF development was defined as improvement of quality of education and providing a unique experience for EPFL students. At the beginning the main goals of the EPFL CDF were:

- Teaching of the classes offered by the Space Center;
- Systems Engineering studies in fields of Space Systems, Aeronautics, Mechanical Engineering, Robotics and other fields;
- Support for the Swiss Cube project - unified implementation of computer models;
- Facilitate interaction between Swiss industries and the European Space Agency and teaching courses for the space related industry.

Facility description



The EPFL CDF has been based on ideas developed by the European Space Agency Concurrent Design Facility (ESTEC, [*Bandecchi et al.*, 1999]) and the TeamX project [*Moeller et al.*, 2010] at the Jet Propulsion Laboratory. Room layout and computer software have been adapted to implement efficient facility in an academic setting and introduce Concurrent Design to students and faculty.

Equipment

The CDF room contains 10 desktops and 3 workstations. Each subsystem is capable of showing its data on the screen and the facilitator can switch between various subsystems. There are 3 projectors and 2 SmartBoards. Interaction with computer and data are done via use of SmartBoards.

Software

Software is a set of Excel macros, inspired by the ESTEC's CDF model. We have implemented this software and included interaction between various software packages to improve productivity during sessions. The system is currently capable of interfacing with STK, MATLAB and CATIA software packages. Since the release of specifications for OCDS server, we now integrating our models with new standards. The software allows to introduce as many parameters for the system and yet summarize necessary data for the most important trades. For example, system engineer can easily access mass and power budget, telecom data rates etc.

We have also implemented a system to assist with tracking of the requirements. All requirements are entered into a database (MySQL) via a specialized interface on an Excel sheet. The interface allows to initiate, edit, confirm or validate requirements. User level access is controlled, hence subsystem engineers only have access to requirements from their subsystem. External systems can be used for tracking requirements and understand dependencies between different levels.

One of the problems in concurrent design is to back track to a particular decision point, or understand why a particular decision was taken. A simple version control system is implemented, based on the Subversion (open-source version control system). Before committing a design or design change the engineer needs to enter a simple log, which can be later retrieved together with the spreadsheet. It requires a certain discipline in the team, but it allows to keep the history of design evolution.

To allow efficient exchange of parameters and modification of designs during session, subsystem sheets are linked directly with engineering tools used at the Space Center. Currently, we have linked CATIA (Computer Aided Three-dimensional Interactive Application, by Dassault Systemes) for the structures subsystem. STK (Satellite Toolkit by Analytical Graphics, Inc) is used for mission design, power and telecommunications subsystems. Some specific models are being implemented in MATLAB software suite (by MathWorks) and data are being exchanged by means of an XML file. In some projects a model written in MATLAB may become the centerpiece of design evaluation, in which case there are practically no calculations that are performed in Excel and all models are implemented directly in MATLAB (Figure 1).

In the near future, we are planning to evaluate use of the Open Concurrent Design Server [*Mathyssen et al.*, 2010] for projects carried out in academic environment. This will require a major software change and redesign of existing interfaces. We also plan to improve handling of requirements and design logs. Migration to OCDS will allow development of models, that can be exchanged with ESA CDF and possibly other universities.

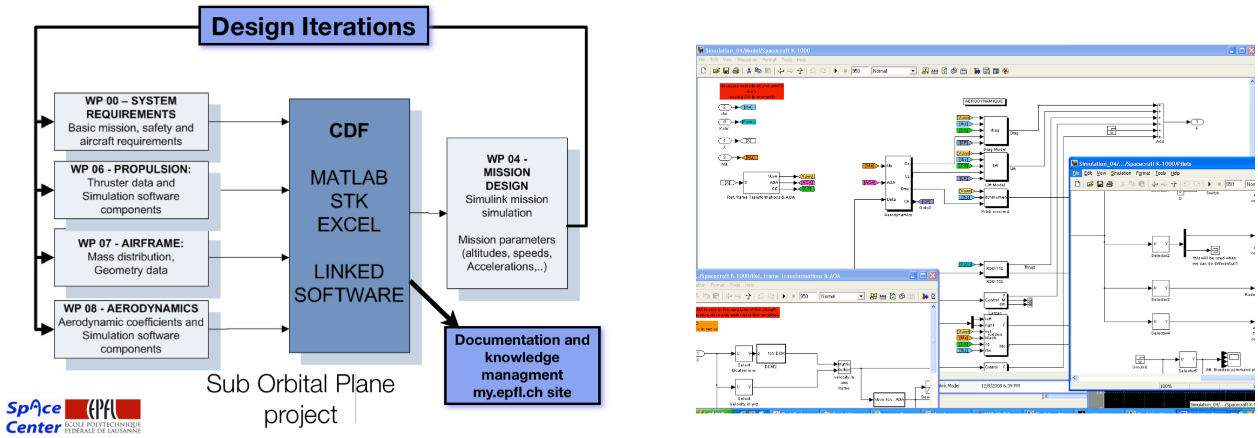


Figure 1. Design of interface between Excel and Simulink/Matlab. a) An overall overview of a concurrent design procedure employed for the design of a suborbital plane. Excel worksheets are used as a GUI for engineers to do simple calculations and enter design parameters. Most of the simulations are performed offline by MATLAB/Simulink model and major design parameters are communicated back to Excel. Some details of model implementation are shown on panel b). Figures adopted from [Reto Wiesendanger, 2009]

Design projects

The Concurrent Design facility was designed from the beginning to address problems in complex systems engineering which is not constrained by applications in spacecraft design. During a university semester we tasked students to develop their own models and combining them into system to conduct trade studies. The nanosatellite study project, which follows classic lines of work at ESA or NASA, was aimed at creating versatile tools to model 1U and 3U Cubesats for Earth Observation of technology demonstration. K1000 project is a project design a sub-orbital plane, in which passengers can experience 0g environment. The Hybrid Motorcycle project aimed at developing a highly efficient two-wheeler, where braking energy will be used to charge up electrical battery. These projects cover a wide range of disciplines,which are taught at the university. In particular, we benefit from expertise in Mechanical Engineer, MIcroelectronics, Power electronics and other fields.

Use of the CDF for education purposes implies that it is not possible to rely on consistent help of a team of experts, who are available from technical divisions. Also nature of the projects changes every semester, as will be shown below. The solution lies in training of the team during the 14 weeks of the semester. Over the course of semester project or master project work, students develop their models, which are then integrated in CDF environment. Sometimes, it is possible to continue development of models over two semesters (e.g. K1000 project) but the team has be trained anew. Although one study takes considerably more time compared to, say, ESA CDF, the main educational goals are attained. Students gain an important technical experience and how to work on a complex problem in a team oriented environment.

NanoSatellite

The goal of this project was capture design of the SwissCube subsystems and construct 1U to 3U models to be used in a concurrent design facility. All models presented below were validated with results obtained by the SwissCube project during testing or operations. We present some general results obtained by telecom (space segment), structures, attitude control and command and data management subsystems. Other models (e.g. systems, mission design, power) were also developed but are not discussed here.

Telecom (space segment)

This work was to estimate the maximum data rate for a nanosatellite, which depends on many parameters (frequency, distance, Tx power etc). Our goal was to optimize telecom board components to provide highest possible signal-to-noise and to have sufficient S/N_0 form the demodulation with power constraints of a nanosatellite.

The telecom Excel sheet is setup to analyze many basic parameters (SNR, Gain, Power absorption etc), but the temperature coefficient aren't taken in account (frequency stability and power absorption, vs temperature can't be analyzed. The power absorption are taken from the components data sheet and the real value value can be different, but it can give however a good idea of what it will be the final consumption of the board. The dimensions are also taken form the IC data sheet and add some extra near components, and we can estimate the total dimension of the board. Final design of the card allows variable data rate of up to 9600bps for a satellite on a 700km orbit. Such design allows to maximize daily data volume downloaded from the satellite, over a standard board which has a fixed data rate of 1200bps.

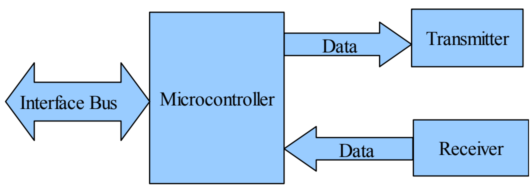


Figure 2. Typical Block-scheme of a COM board on the satellite. Each block is modeled at a high detail level (components) to provide understanding of the board behavior in different conditions. [Belloni, 2009]

Structure subsystem.

A structure subsystem for nano and microsatellites was established and six satellites were designed: one 1UCubeSat, three 3UCubeSats, one cubic and one octagonal microsatellite. It consists in a CDF interface and two CATIA assembly. The CDF interface is the connection part between the CATIA assemblies and the CDF database. It enables the change of dimensions of the parts and synchronizes them with the CATIA assemblies.

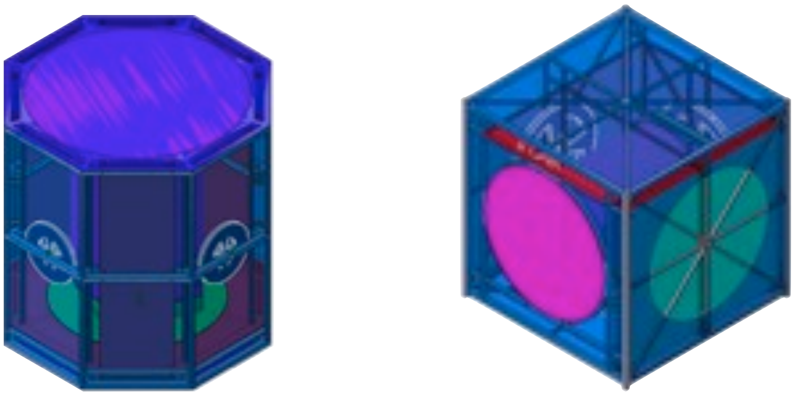


Figure 3. 3D CAD drawings for microsatellite structures. Characteristic size is 40cm. These structures are parameterized and their size can be changed by varying a parameter in an Excel worksheet. These structures can also be tested for stability and vibration using a Finite Element Modeling technique. [Füglistaler, 2009]

The first CATIA assembly is a 3D representation of the satellite and is used to calculate the mechanical properties of the satellite: its mass, volume, surface, center of gravity and matrix of inertia. The second CATIA assembly is used for FEM analysis. The 3D parts for the panels, PCBs and motherboard were replaced by 2D shells and the 3D parts for the spacers were replaced by 1D beams.

Design	Weakest points
1UCubeSat	PCBs
Circular 3UCubeSat	PCBs
Cubic microsatellite	PCBs Panels Frame: crossbars
Octagonal microsatellite	PCBs Frame: sidebars Frame: inertial Wheel attachement

Table 1. Weakest design points of a microsatellite design. All structures were subjected to modeling of a vibration test based on specifications for different launch vehicles. Von Mises stress values on all parts of the structure were used to rank weakness across the structure. This test allows to identify and reinforce areas where problems may arise during launch. Adapted from Fueglistatler, Table 6.20.

Four type of FEM analyses were performed: static loads, modal analysis, harmonic and transient dynamic responses. The FEM results were verified by varying mesh sizes and comparing the 1UCubeSat's results with SwissCube. For the 1UCubeSat design, the SwissCube results were reproduced. The results of the other satellite design give a first order overview of their reaction to static loads and their eigenfrequencies. All values are well within the requirements and the weakest points were spotted.

Attitude determination and control

The main goal of the project has been the development of a designing tool concerning the ADCS of a nanosatellite. The methodology consisted of two major parts: the "modeling" of the satellite as a dynamical system controlled by the actuators, and the "database" of hardware needed to do so.

This modeling of the attitude control system considered the following topics: Frames, conservation laws (conservation of angular momentum), establishment of the dynamical model, control architecture, definition of the type of controller, the feedback, and choice among open loop or closed loop options. The models were implemented in MATLAB and verified vs. SwissCube parameters.

The sensor and actuator database was developed to support modeling of the attitude control system. The tables are implemented as an Excel sheet. The Excel interface allows to use different hardware parameters, which are then used by the MATLAB model to evaluate system performance.

Command and data management system

CDMS model was developed on the basis of the SwissCube design. Particular attention was paid to the power consumption of the board and optimization of its characteristics to accommodate payload requirements. CANbus and I2C bus architectures were considered. Components database was created that allows to model various configurations of processors and memory depending on satellite requirements. This model was validated using SwissCube design.

Satellite studies

Models described above were used to to conduct trade studies to consider different options for launch vehicle for a 1U cubsat. Another project is looking at different architectures for a 3U satellite. Science requirements are set to design a 3U satellite can carry payload that satisfies requirements of the international climate monitoring community for Global Earth Observation (e.g. a spectrometer). In the future, we are planning to scale some of the models to consider microsatellite architectures. Some systems will not scale and therefore will be redesigned using existing connections with design tools.

Sub-orbital space plane

This project was to design a sub-orbital plane, in which passengers can experience 0g environment. The plane is deployed from a commercial plane at the altitude of 10km and then uses its own engines to climb up to altitude of 100km. After a few seconds of microgravity environment the plane glides to a safe landing. This project consisted of a mechanical, aerodynamics and propulsion subsystems. General view of the plane is shown in Figure 4. Overall plane and mission parameters were all collected in a system sheet. The team has computed aerodynamic properties of the space plane and validated primary requirements of the project.

The main focus of the study was safe return of the plane with the passengers. Acceleration loads must have not exceed 5g. These requirements were reflected across the system in shape of the plane, control algorithms for descent and landing as well as operational constraints.

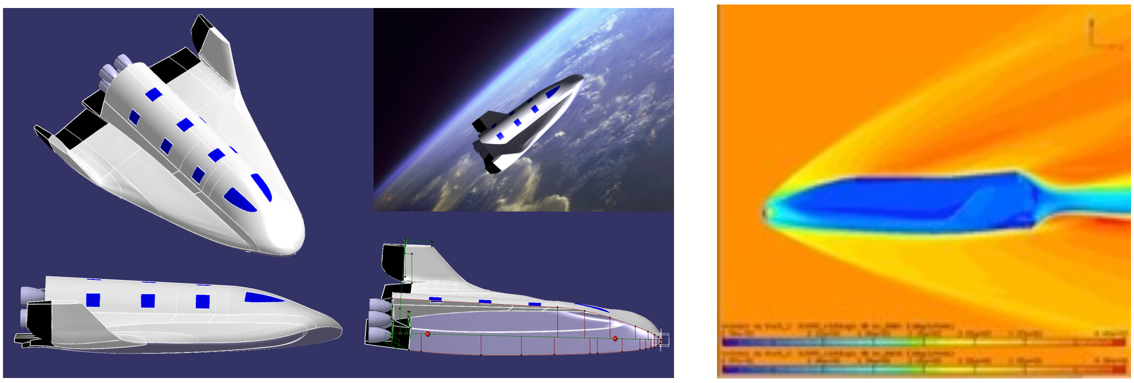


Figure 4. Snapshots of external view of the sub-orbital space plane (left panel) and an example of aerodynamic flow simulation. Shape of the airplane was used in flow calculations to determine a set of aerodynamic coefficients.

During this study we have implemented a centralized model approach for the Concurrent Design. In contrast with classic modeling, where subsystems models are implemented independently, we employed a central model for the system written in MATLAB/Simulink environment. Each of the subsystem engineers was responsible for contributing a submodel block to the system and the role of systems engineer was to integrate all inputs. We have found that for clarity all of the important parameters shall stay in the Excel sheet, which was used as input table. Excel sheets were also used to summarize model results. This approach allowed very efficient implementation of complex design loop, which included some very demanding computations of aerodynamic properties of the vehicle. Structural shape of the plane was designed by mechanical engineers. Using this shape, aerodynamic coefficients were computed on a cluster system. Results of aerodynamic simulation were then used for control algorithms and mission design.

Once model was established we performed studies on secondary propulsion system (for improved security of the descent and landing), some aspects of vehicle and passenger safety, prepared examples of the flight failure tree and possible outcomes. Through extensive use of visualization tools linked to the model we have also made recommendations for improvement of customer experience.

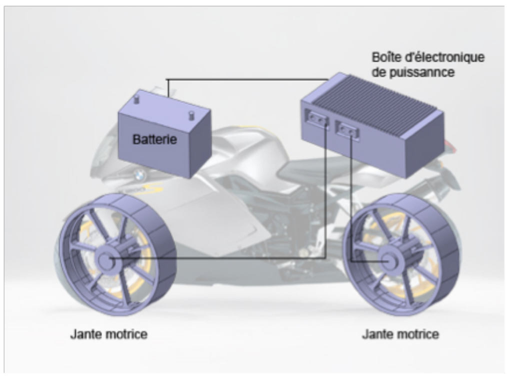


Figure 5. General schematics of subsystems that were designed during this study. We have implemented the motorized wheel, battery and power/control electronics subsystem.[Reto; Wiesendanger and Locher, 2008]

Hybrid motorcycle

Mechanical Engineering section conducts group projects (4-8 students) during a length of one semester, which are also known as HOMOFABER. One of these projects was carried out a the Space Center Concurrent Design Facility. This project's goal is to construct an upgrade kit for a motorcycle to take advantage of an electric motor and kinetic energy of braking. Students have developed models in Matlab, Simulink and CATIA. This was again an approach with a centralized model, which implemented movement of the motorcycle on a predefined track (mountain route) to calculate consumption of fuel. Optimization parameters were weight of the battery, components for the power electronics block and type of a motor used in the motorized wheel. All different components were considered together as an upgrade kit to a regular motorcycle. Final results indicated that total weight of the upgrade kit will 20kg and fuel savings will be negligible. This project has proven to be an excellent educational tool for 3rd year mechanical engineering students, which was their first experience in working in a team.

Conclusions

The Space Center EPFL Concurrent Design Facility was implemented in an academic environment. We have discovered that we have to train our own team of experts and develop our own model each semester. Quality and scope of a study is improved significantly. if a master degree student is in the team. Although the length of a typical study is much longer than in industry, education and research goals are attained. We were also able to adapt to any type of project that allowed ready collaboration with an industrial partner. In this context the CDF was used as teaching and research laboratory. The Space Center EPFL CDF has been operational for last two years. We have shown that the concept of Concurrent Design can be applied to space systems engineering and other fields (mechanical engineering, aerospace). Our CDF is also used to teach the process of systems engineering. We have gained significant experience on how to engage students and how to include CDF studies into curriculum. While there is no pressing time constraint, we have additional focus on interaction in the team, writing technical reports and documentation.

Concepts of the systems engineering and concurrent design were adjusted for the academic environment. We have successfully proven that it is possible to extend the framework behind space-only studies, providing a flexible data/model environment. Students can now obtain an experience in complex project and solve real-world problems.

Bibliography

Bandecchi, M., B. Melton, and F. Ongaro (1999), Concurrent engineering applied to space mission assessment and design, *Esa Bulletin-European Space Agency*(99), 34-40.

Belloni, F. (2009), Nanosat COM board design, EPFL, Lausanne.

Fijneman, M. (2010), Concurrent Design Applications in Construction, Offshore Industry and Engineering Education, paper presented at SECESA 2010, Lausanne.

Füglistaler, A. (2009), Conception of nano-satellites in a concurrent design environment, EPFL, Lausanne.

Mathyssen, A., S. Gerené, and H. P. de Koning (2010), Initial Results from Application of the Open Concurrent Design Server (OCDS), in *SECESA 2010*, edited by ESA, Lausanne.

Moeller, R., C. Borden, T. Spilker, W. Smythe, and R. Lock (2010), JPL's Rapid Mission Architecture (RMA) Team and Methods for Space Mission Trade Space Generation, Exploration and Assessment, in *SECESA 2010*, edited, Lausanne.

Wiesendanger, R. (2009), Mission Design for a Suborbital Plane, EPFL, Lausanne.

Wiesendanger, R., and T. Locher (2008), Projet Moto Hybride, Space Center, Lausanne.