MUSTANG 0
A low-cost technology demonstration nanosatellite
Summary of the Group Design Project
MSc in Astronautics and Space Engineering
2004/05
Cranfield University

College of Aeronautics Report 0502

ISBN 1 861941 22 6

Dr. Stephen Hobbs
Cranfield Space Research Centre
School of Engineering
Cranfield University
Cranfield
Bedford MK43 0AL UK
s.e.hobbs@cranfield.ac.uk

8 August 2005

Abstract

Students of the MSc course in Astronautics and Space Engineering 2004/05 at Cranfield University took Mustang 0 as their group project. This report summarises their findings. Mustang is a partnership of several groups interested in technology for small spacecraft: Mustang 0 is intended to be a simple spacecraft suitable for technology demonstration (especially highly miniaturised systems based on MEMS or microsystem technology (MST)). A parallel student project took place in the School of Industrial and Manufacturing Science at Cranfield University to investigate MST available from non-space sectors and the qualification process for space hardware.

Design studies have been performed for all the spacecraft sub-systems and build on previous work by Mustang partners. The spacecraft designed has a mass of just less than 10 kg, a lifetime of 1 year, is 3-axis controlled, and could be launched to either GTO or LEO. New areas studied this year include software design and operations, and some hardware (the main structure) has been manufactured.

The project conclusion is that a low-cost (< £ 100k for a flight-ready spacecraft) technology demonstration mission is possible. The Mustang 0 study identifies no fundamental problems, although a significant amount of work remains. Many sub-systems now require prototyping to validate and develop the proposed designs.

ISBN 1 861941 22 6

This report is available electronically from Cranfield University's QUEprints service (`https://dspace.lib.cranfield.ac.uk/`).

Acknowledgements

The work presented in this report is primarily that of the MSc students whose work is summarised in Appendix D. The project was supervised by Drs Hobbs and Kingston of Cranfield Space Research Centre. It is a pleasure to thank all those outside Cranfield University who have contributed to the project in some way.

Steve Eckersley of EADS Astrium UK Ltd. supported the project and gave technical help and guidance on possible mission objectives (he also supported the parallel project on space qualification of MST components in SIMS). Many space industry professionals around the world have responded promptly and willingly to enquiries from the students and are much appreciated for their encouragement.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Mustang 0 is the topic of the one of the two group projects for the 2004/05 year of the MSc in Astronautics and Space Engineering at Cranfield University. Mustang is a partnership of groups (Cranfield University, Southampton University, EADS Astrium UK Ltd.) interested in miniaturised technology for spacecraft, and Mustang 0 is a project to design a low-cost satellite suitable for technology demonstration.

This report is a summary of the project, and mainly consists of a compilation of the executive summaries written by the students for their individual reports. These summaries (only lightly edited) provide a good overview of the individuals' work and also act as an index to the full reports (available from the School of Engineering, Cranfield University). (*Readers should be aware that although gross errors in the individual reports should have been corrected, no responsibility can be taken for the technical work presented.*)

1.1 Organisation of the Project

The project runs over the first two terms (October to Easter) of the year long MSc course in Astronautics and Space Engineering at Cranfield University. The students work as one team, organised as several subgroups, and each student contributes about 600 hours' effort to the project; the total resource represented by the project is approximately 10 000 hours' work for the academic year 2004/05.

1.2 Starting Point of the Project

Appendix A is the main document given to students at the start of the project in October 2004. It summarises the status of Mustang's work, provides a list of available resources (e.g. previous project documents, related "nanosatellite" mission studies), and states the project's objectives.

1.2.1 Mission requirements

Mission requirements are based on the following aims and objective provided at the outset of the project. Mustang 0 has two aims (quoted from the initial project document, Appendix A):

- to produce a simple technology demonstration nanosatellite suitable for MST experiments (devices and concepts),
- undertake studies of space MST system issues to ensure the technology demonstration hardware develops key competences relevant to the longer term goals in this area.

Related to these aims, the project objective is stated as:
The key objective is to design a nanosatellite mission (using available hardware and a level of technology appropriate to a university nanosatellite) which will provide suitable benefits/enablers for an on-going programme of space MST.

The proposed mission should therefore not be seen as a "stand-alone" project, but must be useful in the context of a continuing sequence of future nanosatellites. Specific interests flagged by Astrium include:

- Future mission studies (formation flying for science, communications, imaging)
- Nanosatellite system cost modelling
- System issues for future missions (communications, power, thermal, . . .)

Other interests:

- Issues of system architecture, especially related to issues such as collaborative working, robotics, autonomy, communications architecture, and derived requirements on the s/c themselves.
- Perhaps design / develop prototypes of demonstrators for formation flying or collaborative working?
- Studies to relate Mustang 0 to longer-term goals in space MST: especially in the areas of formation flying and planetary sensing (building on other current interests).

Project decisions and trade-offs should be made with reference to the benefits (in terms of technology demonstration, lessons learned, or validation of techniques), for future projects.

1.3 Structure of this Report

Following this introduction there is an overview of the technical work carried out by the team. The overview considers each technical area of the project in turn and concludes with a synthesis based on the system studies. The final chapter (Conclusions) states the project's main findings and outlines areas requiring further study.

Appendices contain all the executive summaries written by the students and summarise the mission and the project organisation.

Chapter 2

Technical Work

The following sections summarise the technical work performed by the students for Mustang 0. Details are contained in the individual report written by each student.

2.1 System

Although the system engineering tasks are in some ways the most important they can also be the least glamorous and with least to show in terms of “hard” results, i.e. the specific designs developed at sub-system level. The system engineers this year have developed an outline system model (Excel spreadsheet) and have given more attention to the cost of the spacecraft. These are in addition to the usual tasks of maintaining all the system budgets (power, mass, etc.) and coordinating the system-level design trade-offs.

2.2 Payload

Some new payload concepts have been proposed (e.g. a mobile telephone for low-cost communications) and the interface document has been updated. Students of the Nanotechnology MSc (School of Industrial and Manufacturing Science) have developed a design for a sun sensor which could be carried as a payload.

2.3 Electrical

Compared to previous years, the areas which have seen most concerted effort in 2004/05 were the electrical sub-systems. There were two students each on (a) electrical power, (b) data handling, and (c) communications. These are areas in which there is relatively weak local expertise and so a careful balance must be struck between the ambition of the design and the local capabilities. At a system level decisions have to be made concerning the alternatives of (1) developing equipment locally or (2) through a partner organisation, or (3) purchasing COTS products.

2.3.1 Power

The power system design has been refined and now includes a more detailed design for the power regulation circuits. The configuration of solar cells around the spacecraft has been evaluated in some detail to maximise power raising while making use of readily available commercial cells of high efficiency.

2.3.2 Data Hardware and Software

For the first time, the data handling system *software* has been the subject of study. The hardware design follows that proposed earlier (using the I2C serial bus) and using a space-qualified processor. The chosen processor is relatively power-hungry and so a lower power system may eventually be required.

The serial bus architecture allows the data handling system to be developed incrementally from a prototype based on desktop PC's to the eventual flight system. It is important to develop a robust and versatile architecture for the *software* of the data handling system so that the advantages of the bus hardware design are fully exploited. In practice this requires good modularity so that changes of specific technologies (e.g. the bus standard) only have local impact (e.g. only on the functions handling bus communication), and also so that sub-system specific software (e.g. AOCS, payload, thermal control) can be developed in parallel and devolved to the relevant sub-system engineers. The progress made this year exposes some of the issues which will have to be solved in the final version, i.e. payload data handling, system bandwidth, and communication protocols.

2.3.3 Communications

Communications is a key sub-system since unless the communications link works users will know nothing about any payloads being carried. A COTS solution for the UHF waveband was chosen, with a single ground station (which could be built and based at Cranfield).

2.4 Mechanical

Filament-wound structures suitable for Mustang 0 were manufactured and delivered by EADS Astrium during the autumn and have been adopted as the spacecraft structure. The filament-wound structures will be of value themselves for technology demonstration as well as providing a light, strong structure of the right size for a 10 kg nanosatellite.

Based on the actual structures, the structural and thermal design / analysis have been studied for typical launch vehicles and for the various orbit options (principally GTO and LEO).

2.5 AOCS

Although there will be no attempt to control Mustang 0's orbit, it was felt that 3-axis attitude control was valuable enough to be designed into the basic mission.

Attitude control will be based on sun sensors and magnetometers as sensors, and magnetorquers and a reaction wheel assembly as the actuator. The challenges for AOCS design were

1. Lack of precise requirements for attitude control,
2. Need to develop a low-cost solution,
3. Uncertainty about the eventual orbit (especially important for designing a magnetorquer).

The target accuracy chosen was on the order of a degree. This was good enough to enable accurate pointing of the communications antennas, good power raising using solar arrays, and satisfactory testing of basic payloads.

2.6 Discussion

Although a nanosatellite has been the subject of several group project reports, this is the first time that the project has involved hardware suitable for flight (the filament-wound structure).

In many sub-system areas the main design decisions have been identified and it is unlikely that major design changes will be required for the spacecraft as a whole. There is scope to redefine the baseline to keep the spacecraft as simple as possible while still being useful, and consider some of the more "ambitious" technology (e.g. 3-axis control) as payload instead. In this way, new technology could be carried as payload on one mission and then if successful it could be incorporated as part of the main spacecraft on later missions. This lowers risk for the early missions while developing useful capabilities for later ones. The next stage in most areas is to proceed to detailed design and / or prototyping; these tasks are generally more suitable for individual projects rather than MSc group design projects.

There are also lessons to be learnt from the project for future planning of student projects. The intention at the start of the project was that several subsystems would be implemented at prototype level. In practice, the combination of students inexperienced in practical work, the time taken to define adequately detailed designs, the time available to students, and the lead times on delivery of parts, meant that very little was achieved at prototype level. With thorough preparation and active technical support it should be possible to allow all students to make some progress, and good students to make significant contributions to the project. One drawback of this approach is that there will be less scope for student initiative since at least the early steps will be much more tightly defined.

Chapter 3

Conclusions

Progress has been made in all areas of the project, and lessons have been learnt which should make future work more productive. The main conclusions are:

- The general concept of a nanosatellite for technology demonstration seems feasible.
- The outline cost budget of £ 100 k seems reasonable (but requires more detailed analysis).
- Progress to hardware, even at prototype level, will require thorough preparation and some resources. Without appropriate support, it is difficult for MSc students to contribute significantly to this work in the limited time they have available.

3.1 Future Work

In all sub-system areas there is work to be done on detailed design and / or prototyping of the design solutions. Some of these prototypes could evolve into the eventual flight systems. For the project to progress there are several tasks which should be undertaken soon to guide further development:

- System design review to critique the current (March 2005) system design and mission objectives. The partitioning of functions between the "spacecraft" and "payload" and the operational modes defined give many options which have not yet been fully explored.
- The development process from the current design state to a flight-ready spacecraft needs to be defined in some detail. This will give an understanding of the critical path, identify long-lead items, and show how all the tasks should relate to each other. Account should be taken of several credible development scenarios (both optimistic and pessimistic).
- The cost budget should be developed to give a clear understanding of the resources needed to see the project through to completion, to assess its feasibility / the need for external support (of all kinds), and to identify opportunities for significant cost savings.

- Detailed design and / or prototyping of the design at all sub-system levels.
- Develop candidate payloads compatible with Mustang 0 (and noting that other flight opportunities may become available for some payloads).

Bibliography

[1] Baxter, Peter, MUSTANG0, a technology demonstration nanosatellite. Payload interface, operations and identification *Group Design Project Report, MSc in Astronautics and Space Engineering, School of Engineering, Cranfield University, March 2005.*

[2] Bowling, Tom, Space system engineering, unpublished course notes. *School of Engineering, Cranfield University, 2004.*

[3] Burgon, Ross, MUSTANG0, a technology demonstration nanosatellite. Attitude and orbit determination and control *Group Design Project Report, MSc in Astronautics and Space Engineering, School of Engineering, Cranfield University, March 2005.*

[4] Cambronero, Damian, MUSTANG0, a technology demonstration nanosatellite. System engineering - risks and system model *Group Design Project Report, MSc in Astronautics and Space Engineering, School of Engineering, Cranfield University, March 2005.*

[5] Crerar, Robyn, MUSTANG0, a technology demonstration nanosatellite. Structure and configuration *Group Design Project Report, MSc in Astronautics and Space Engineering, School of Engineering, Cranfield University, March 2005.*

[6] Demeure, Axel, MUSTANG0, a technology demonstration nanosatellite. Thermal design *Group Design Project Report, MSc in Astronautics and Space Engineering, School of Engineering, Cranfield University, March 2005.*

[7] Diependaele, Matthieu, MUSTANG0, a technology demonstration nanosatellite. Data and onboard software *Group Design Project Report, MSc in Astronautics and Space Engineering, School of Engineering, Cranfield University, March 2005.*

[8] Dufay, Bertrand, MUSTANG0, a technology demonstration nanosatellite. System engineering - budgets *Group Design Project Report, MSc in Astronautics and Space Engineering, School of Engineering, Cranfield University, March 2005.*

[9] Gannon, Richard, MUSTANG0, a technology demonstration nanosatellite. Operations *Group Design Project Report, MSc in Astronautics and Space Engineering, School of Engineering, Cranfield University, March 2005.*

[10] Haria, Kajal, MUSTANG0, a technology demonstration nanosatellite. On-board communications *Group Design Project Report, MSc in Astronautics and Space Engineering, School of Engineering, Cranfield University, March 2005.*

[11] Koronka, Paul, MUSTANG0, a technology demonstration nanosatellite. Ground communications software *Group Design Project Report, MSc in Astronautics and Space Engineering, School of Engineering, Cranfield University, March 2005.*

[12] Larfars, Kristina, MUSTANG0, a technology demonstration nanosatellite. Power system: generation *Group Design Project Report, MSc in Astronautics and Space Engineering, School of Engineering, Cranfield University, March 2005.*

[13] Marchand, Benjamin, MUSTANG0, a technology demonstration nanosatellite. Ground communication system *Group Design Project Report, MSc in Astronautics and Space Engineering, School of Engineering, Cranfield University, March 2005.*

[14] Soeberg, Philip, MUSTANG0, a technology demonstration nanosatellite. Power system: regulation and storage *Group Design Project Report, MSc in Astronautics and Space Engineering, School of Engineering, Cranfield University, March 2005.*

[15] Wertz, J.R., and Larson, W.J. Space mission analysis and design, third edition. *Microcosm Press and Kluwer Academic Publishers, 1999.*

Appendix A

Introduction to Mustang0

This document was issued to students at the start of the project in October 2004.

ASE Group Design Project 2004-5

MUSTANG 0 Nanosatellite Project

A.1 Introduction

EADS Astrium and Cranfield University have collaborated for several years on research in the general area of microsystems technology (MST) for space applications. Previous work has covered surveys of available technology, nanosatellite design studies, and work on related system concepts such as formation flying and end of life disposal technologies.

The Mustang 0 group project for 2004/05 continues this research, and has two aims:

- to produce a simple technology demonstration nanosatellite suitable for MST experiments (devices and concepts),
- undertake studies of space MST system issues to ensure the technology demonstration hardware develops key competences relevant to the longer term goals in this area.

The project is being run with EADS Astrium as part of their programme of research into space applications of MST.
A parallel project will run at Cranfield in the Nanotechnology Centre (School of Industrial and Manufacturing Science) and the intention is that the two groups should complement each other, although the projects will run largely independently.
This document provides further background to Mustang 0, suggested reference sources, and information about the organization of the GDP.

A.1.1 Project Information

The Group Design Project runs from October 2004 to March 2005. An outline schedule timeline is given later in this document. In the first week, students are expected to decide which of the two project topics (Mustang 0 and the Mars Aeroplane) they would prefer to work on. The aim is to have a roughly 50:50 split of student numbers between the two projects, so it may not be possible for all to get their first choice of project. During this first week, students should also start to think about which Work Package areas interest them most. However, at first this need only be in fairly broad terms, and can be discussed at the second meeting. Work package allocations should be finalised by the third meeting, and each student will then be expected to produce a Work Package Description, detailing WP inputs required, expected outputs, and an overview of anticipated tasks. This will encourage familiarisation with the project, and should identify any "gaps" arising from the allocation of tasks.

A.1.2 Project Meetings

As indicated in the Course manual, there is one GDP meeting timetabled per week. This should be seen as the main forum for exchanging ideas, presenting updates to the whole group, and allocating tasks for the following week. There will generally be at least one member of staff present at these weekly meetings, but the student group is expected to run the meetings themselves, with a Chairman, and Secretary taking minutes to circulate to the group and staff. It is up to the group how they organise selection of Chairman, Secretary etc. In addition, you will need to meet at other times in the week, perhaps in smaller groups, to work on specific tasks as they arise.

A.2 Background

MUSTANG (Multi-University Space Technology Advanced Nanosatellite Group) was the group design project for ASE students for the academic year 2001/02, and built on work from previous years' projects. The project involved the initial design of a nanosatellite to be used as a technology demonstrator for microsystem technology (MST) in space. MUSTANG also involved students from the University of Southampton, and staff at EADS Astrium (UK) Ltd. (Cranfield's School of Industrial and Manufacturing Science and the universities of Cambridge, Imperial College and Oxford were also involved.)

Previous MUSTANG project work has chiefly consisted of theoretical "paper studies". The MUSTANG 0 group project for 2004/05 will be a much more hardware-oriented study, run in collaboration with EADS Astrium. Astrium are providing some hardware for the project, and other equipment may be procured as the project progresses. The aim is to develop a first generation technology demonstration spacecraft as part of a broader programme to develop MST for space applications. The project will therefore have two parts:

1. Mustang0 spacecraft – a simple technology demonstration satellite,
2. MST system studies laying the foundation for more advanced systems.

Note on Terminology:

MST / MEMS refer to the same general area, i.e. miniaturisation of technology down to micron scales, together with a high degree of integration, on-board intelligence (autonomy), etc. The terms do differ slightly however:

- MEMS (micro-electro-mechanical system): sensor / actuator device
- MST (micro-system technology): refers to a higher level of integration including information processing too, i.e. a complete (sub-)system

A.3 Objectives

The key objective is to design a nanosatellite mission (using available hardware and a level of technology appropriate to a university nanosatellite) which will provide suitable benefits/enablers for an on-going programme of space MST. The proposed mission should therefore not be seen as a "stand-alone" project, but must be useful in the context of a continuing sequence of future nanosatellites.

Specific interests flagged by Astrium include:

- Future mission studies (formation flying for science, communications, imaging)
- Nanosatellite system cost modelling
- System issues for future missions (communications, power, thermal, ...)

Other interests:

- Issues of system architecture, especially related to issues such as collaborative working, robotics, autonomy, communications architecture, and derived requirements on the s/c themselves.
- Perhaps design / develop prototypes of demonstrators for formation flying or collaborative working?
- Studies to relate Mustang0 to longer-term goals in space MST: especially in the areas of formation flying and planetary sensing (building on other current interests).

Project decisions and trade-offs should be made with reference to the benefits (in terms of technology demonstration, lessons learned, or validation of techniques), for future projects.

A.4 Anticipated key project outputs

The expected outputs of the project relate directly to the project's objectives:

- System level design of MUSTANG 0 nanosatellite
- Engineering/electrical/breadboard model of significant sections of the spacecraft

- Structural model
- Analysis of the technology used and suggested for future use on nanosatellite

A.5 Initial Work Area Suggestions

The following are some suggested areas for initial consideration and trade-off studies. This is not intended to be a comprehensive list, but should give some ideas to help get the project activity started. Each of these topics is likely to require study of several sub-system areas to identify pros and cons of the different options, and then a trade-off to determine which option best matches the top-level system objectives.

1. Mission lifetime – days, weeks, a year..? Perhaps a shorter baseline mission duration, with the option to extend if the system permits. For example, battery power as a baseline, with a solar cell experiment that could provide longer survival.
2. Orbit selection – LEO, GTO? Look at launch options, the advantages, disadvantages, and opportunities of different orbits. For example, a more severe radiation environment in GTO may be useful to demonstrate radiation hardness of electronics.
3. Test/acceptance philosophy – for example, could numerous identical MST sensors be flown; would this equate to a "longer mission equivalent" and therefore provide a more useful demonstration?
4. Command and communications strategy – will the spacecraft be commandable? Will data be stored on board or continuously transmitted as it is collected?
5. Other topics – it is unlikely that the above areas are an exhaustive list

Following these initial system trade-offs, a baseline mission design will evolve (ideally by early December) and then from January to March more detailed subsystem design / development studies can be performed.

To meet the key objective, a number of contributing objectives may be identified, concerning the mission design philosophy, and the hardware activities. These tasks are some of those the group will have to undertake during the early stages of the project and fall into two categories (System engineering and mission design, and Hardware):

A.5.1 Systems engineering and mission design

1. Identify alternative mission concepts, objectives and payloads
2. Evaluate available hardware, and identify mission architecture options
3. Evaluate the proposed mission in terms of the benefits it will provide to the on-going space application of MST and future nanosatellite missions

4. Identify a suitable mission operations scheme, perhaps allowing for a longer "enhanced mission" if the system can be made to survive longer than the baseline
5. Examine alternative hardware options, and identify limitations of current hardware and more appropriate candidates for the future
6. Characterise what equipment would be suitable/unsuitable for flight use
7. Identify the qualification/risk/redundancy philosophy for the MUSTANG 0 spacecraft

A.5.2 Hardware

1. Understand and characterise the operation of a range of subsystem equipment; the objective should be to develop demonstration system: either protoflight or engineering model for each sub-system area, i.e. not just paper studies.
2. Demonstrate and validate data communications between spacecraft subsystems
3. Produce a structural model of the MUSTANG configuration, using the Astrium structure and representative dummy masses and fastenings
4. Testing of structural model (sine sweep to identify natural frequency and compare to FE model)
5. Simulate operation of a complete spacecraft system, using as much representative hardware as possible
6. Enable the in-orbit validation of EADS Astrium "Micropacks"

A.6 Overview of Work Package Descriptions

The Work Packages given in the table on the following page are a guideline to get the project started. When students have selected a particular WP area, they will be expected to produce their own full work package description. It will then be the responsibility of the Systems Engineers to ensure that there are no gaps or duplication of effort.

A.7 Project Schedule

The following tables summarise the expected project schedule (note the project presentations which are important milestones). In broad terms, the system level studies are the main activity from October to December and then from January to March students are mainly concerned with detailed sub-system studies / development.

WP	Title	Number of students	Remarks / suggestions
1000	System engineering	2	Budgets, WP interfaces, project timeline
2000	Payload	1	Interfaces, accommodation, operations, candidate payload identification (e.g. MEMS devices, deorbit demonstration)
3000	Operations	1	Operational mode definitions, mission timeline, launch arrangements, legal / operational regulations, ...
4000	Structure & Thermal	2	4100:Configuration (inc. fixings, detailed layout) 4200: Structural analysis (primary responsibilty): static and dynamic analysis re launcher requirements) 4300: thermal
5000	Data & communications	2	5100: communications hardware (s/c and ground) 5200: Data and software (s/c and ground)
6000	Electrical	1-2	6100: power 6200: Data handling hardware
7000	AOCS	?	Define measurement requirements Attitude / orbit control actuators (passive / active system)
8000	Manufacture & AIT	1-2	Outline manufacturing procedures to be consistent with flight requirements AIT planning

Table A.1: Mustang0 proposed work packages

A.8 Resources Available

Resources available include the university facilities (laboratories and clean-room) and some satellite components from Astrium.

A.8.1 Hardware Expected to be Available

The following gives an idea of the hardware we expect to be available for the project:

- Filament-wound carbon fibre structures, octagonal prism shape – suitable for spacecraft primary structure.
- Mobile phone components for communications
- Miniature camera
- Temperature sensors
- Accelerometers and/ or microgyros
- Miniature actuators
- Microcontroller
- Thermal blankets (MLI)
- Small pieces of honeycomb panel (for secondary structure)

Week	/ date	Phase	Remarks
1	4 Oct 2004	Introduction	Choose one of the projects this week
2		Familiarisation	Select work package
3			Work packages allocated at third meeting
			Meeting with SIMS students on allied Astrium project
4			Present WP descriptions
5–9	1 Nov 2004	System eng.	Hardware available
10	6 Dec 2004	PDR	Present work to date; interim report to Astrium
2	24 Jan 2005	Recapitulation	Resume GDP
3–8		Detailed design & development	Studies of detailed project design / prototype development
9			Final presentation
10	24 Mar 2005		Submit final GDP reports

Table A.2: Mustang0 proposed timeline

- Fixings
- Electrical wire
- Flight approved crimps (possibly connectors)
- Flight approved tie-bases and tie-wraps for securing harness
- Small quantities of kapton tape and eccoshield tape heaters

A.8.2 Facilities

A number of facilities are available at Cranfield for integration and testing of the spacecraft equipment. The Space Lab is situated on the ground floor of Building 52, and has quite a lot of bench-testing space, electrical test equipment, and several PCs. Also in the same building is our Class 100 000 clean room, which can be used for flight items and any optical equipment which requires a clean environment for test and assembly. Details of cleanroom procedures will need to be obtained before students are permitted to use this facility.

A network of PCs is available in the Space Lab to simulate the data handling and communication sub-systems. This will allow the development of the data handling, communications and operations work packages to progress beyond paper studies. The network currently uses the I2C serial databus proposed by the original Mustang studies.

We also have access to a small mechanical shaker which can be used for sine vibration sweeps. This can be used to validate FE models of the spacecraft structure.

A.9 Reference List for Mustang0

These books and articles give useful background information on nanosatellites, MST, MEMS and especially their application to space or aerospace. Most are available electronically or from the Kings Norton Library. (This is based on a reference list provided by Faye Andrews, EngD research engineer.)

A.9.1 MST / MEMS

AeroAstro Inc. (2000), *AeroAstro Spacecraft Products,* available at: `http://www.aeroastro.com/spacecraft-nano-page.html` (accessed 2004).

Alkalai, L. (2000), 'Advanced Microelectronics Technologies for Future Small Satellite Systems', *Acta Astronautica,* Vol. 46, No. 2-6, pp. 233-239.

Berry, E. (1997), 'Miniaturizing Spacecraft Power and Electrical Systems', in Helvajian, H. and Robinson, E.Y. (Editor), *Micro- and Nanotechnology for Space Systems*, Aerospace Press Monograph 97-01, Los Angeles, pp. 35.

Gad-el-Hak, M., (editor), The MEMS handbook. CRC Press, 2002. (Cranfield University Library classmark 62-187.4 MEM; ISBN 0-8493-0077-0; available as an electronic book from Cranfield University Library)

Helvajian, H. (Editor) (1999), *Microengineering Aerospace Systems*, Aerospace Press, El Segundo, California. (Cranfield University Library classmark 62-187.4 MIC; ISBN 1-884989-03-9)

Helvajian, H., (Editor), Microengineering technology for space systems. The Aerospace Press, monograph 97-02, 1997. (Cranfield University Library classmark 629.78 MIC, ISBN 1-884989-05-5)

Iannotta, B. (1999), "Pocket Rocket", *New Scientist,* No. 10 April 1999, pp. 38-40.

Kawada, Y., Takami, Y. and Fujita, T. (2000), 'New Micro Satellite Concept for Observation Missions', *Acta Astronautica,* Vol. 46, No. 2-6, pp. 159-167.

Lyke, J.C., Michalicek, M.A., and Singaraju, B.K. (1995), 'MEMS in Space Systems', *International Conference on Integrated Micro/Nanotechnology for Space Applications,* Houston, Texas, NASA / Aerospace Corporation, pp. 1-10.

Maluf, N., An introduction to microelectromechanical systems engineering. Artech House, 2000. (Cranfield University Library classmark 62-187.4 MAL; ISBN 0-89006-581-0)

Miller, L.M. (1999), 'MEMS for Space Applications', *Symposium on Design, Test and Microfabrication of MEMS and MOEMS,* Paris, pp. 2-11.

Muncheberg, S., Krischke, M. and Lemke, N. (1996), 'Nanosatellites and Micro Systems Technology - Capabilities, Limitations and Applications', *Acta Astronautica,* Vol. 39, No. 9-12, pp. 799-808.

Panetta, P. and Esper, J. (1999), 'Enabling Technologies for Nano-Satellite Constellations', *IAF Specialist Symposium - Novel Concepts for Smaller, Faster, Better Space Missions,* Redondo Beach, California, pp. 1-9.

Torres, J., Ferrer, C., and Paris, L. (1996), 'Nanotechnology and Nanosatellites', *3rd Interational Symposium on Small Satellite Systems and Services,* Annecy, France, CNES, pp. 1-8.

Yarbrough, A.D. (1997), 'Applying Micro-/Nanotechnology to Satellite Communications Systems', in Helvajian, H. and Robinson, E.Y. (Editor), *Micro- and Nanotechnology for Space Systems*, Aerospace Press Monograph 97-01, pp. 17-29.

A.10 Nanosatellite Data Handling Systems

Cranfield MSc in Astronautics and Space Engineering group design project reports: David Deering (2001/02)

Hobbs, S.E., and Turner, R., CUSTARD, A microsystem technology demonstrator nanosatellite. Summary of the group design project MSc in Astronautics and Space Engineering 1999-2000, Cranfield University. College of Aeronautics report 0019, Nov 2000. ISBN 1 861941 01 3. Available electronically: `http://hdl.handle.net/1826/70`

Hobbs, S., Bowling, T., and Roberts, P., Mustang 2001, Summary of the group design project, MSc in Astronautics and Space Engineering 2001/02, Cranfield University. College of Aeronautics report 0206, Cranfield University. ISBN 1 861940 99 8, Digital Object Identifier (DOI) `http://hdl.handle.net/1826/69`, Sept 2003.

Palmintier, B., Kitts, C., Stang, P., and Swartwout, M., A distributed computing architecture for small satellite and multi-spacecraft missions. SSC02-IV-6, 2002. (Available electronically from `http://aria.seas.wustl.edu/SSC02/papers/iv-6.pdf`)

A.11 Other University Nanosatellite Projects

Cubesat (Aalborg University, Denmark): `http://www.cubesat.auc.dk/`
CubeSat (California Polytechnic State University, Stanford University, USA): `http://cubesat.calpoly.edu/_new/index.html`

Emerald (Stanford University, USA): `http://ssdl.stanford.edu/Emerald/index.htm`

Several other proposed satellite missions are listed at
`http://www.amsat.org/amsat/sats/n7hpr/future.html` and
`http://directory.eoportal.org/res_p1_Satellitemission.html`

S:\yr2004\Mustang 0 GDP Intro.doc, 1 Oct 2004

A.12 Other documents provided

Copies of the following documents were also provided:

1. EADS Astrium micropack description

2. SIMS Nanotechnology application note: Nanotechnology group activity overview
3. SIMS Nanotechnology application note: Microsystems design

Appendix B

Organisation of the Project

The division of responsibilities of the project between the students taking part in the project is described in the following table.

WP	Description	Student(s)
1000	System engineering	Damian Cambronero
		Bertrand Dufay
2000	Payload	Peter Baxter
3000	Operations	Gannon
4000	Structure & Thermal	Crerar (structure)
		Demeure (thermal)
5000	Data & communications	Diependaele (on board s/ware)
		Haria (on board comms.)
		Koronka (ground s/ware)
		Marchand (ground comms.)
6000	Electrical	Larfars
		Soeberg
7000	AOCS	Burgon
8000	Manufacture & AIT	(system eng. responsibility)

Table B.1: Mustang0 work package breakdown and allocation.

Appendix C

Mission Summary

The main objective of the mission is described in section 1.2.1.

Figure C.1 is a general view of the spacecraft, and the following tables summarise the main characteristics of the baseline mission (as at March 2005).

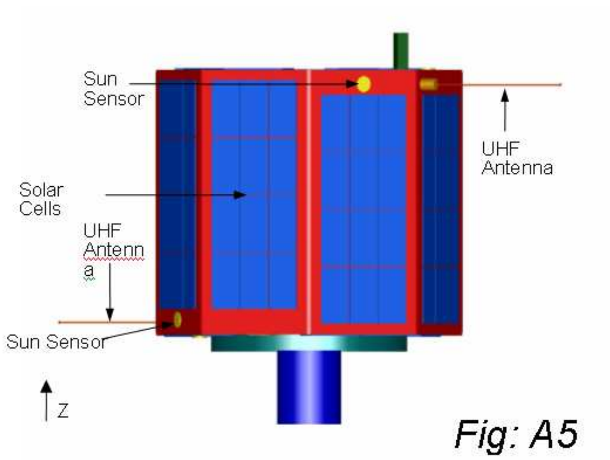


Figure C.1: General view of the Mustang 0 spacecraft (Crerar, 2005).

Shape	Octagonal
Mass	8.335 kg
Power available in light	26.4 W
Consumption	Depending on the mode of operation
Cost (platform)	£ 75,771
Cost (spacecraft)	£ 80,196

Table C.1: Main characteristics of Mustang 0 at conclusion of the project [8].

Operation		Frequency
System Monitor		Every 20 minutes
Reaction Wheel Dumping		Daily, at the very least
Communications		Dependent on orbit and inclination
Payload testing	Camera	Weekly
	Mobile Phone	Weekly
	Dosimeter	As often as possible
	De-orbit Device	Once

Table C.2: Repeatable operations and frequency of occurrence [9].

	Safe	Eclipse	Normal	Comms	Payload	AOCS
Power / W	10.93	15.40	15.40	19.03	15.75	16.54

Table C.3: Power consumption for the different modes [8].

	mass / g	cost / GBP
CFRP tube	1200	5000
Internal panel	1110	40*
Bulkheads	420	200
Fastenings	700	200?
Total	3420	5540

Table C.4: Cost and mass budgets for the structure of MUSTANG 0 [5].

Appendix D

Individual Report Executive Summaries

Executive summaries for all the project reports are given in this appendix. Full copies of the reports may be referred to at the School of Engineering, Cranfield University, UK.

The summaries have been only lightly edited. The reports have been examined and gross errors that were identified have been corrected. However, it is not possible to guarantee that no errors remain; users of the summaries and reports should bear this in mind.

The reports are ordered alphabetically by author surname. Table D.1 lists the students are their individual responsibilities within the project.

Student	Work area
Baxter	Payload [1]
Burgon	AOCS [3]
Cambronero	System engineering [4]
Crerar	Structure [5]
Demeure	Thermal analysis and design [6]
Diependaele	On-board software [7]
Dufay	System engineering [8]
Gannon	Operations [9]
Haria	Communications: on-board [10]
Koronka	Ground software [11]
Larfars	Electrical power: generation [12]
Marchand	Communications: ground [13]
Soeberg	Electrical power: regulation [14]

Table D.1: Sub-system responsibilities for each student

D.1 MUSTANG 0: Payload Interface, Operation and Identification (Peter Baxter)

D.1.1 Abstract

This summary details the ongoing development of the payload section of the MUSTANG 0 Group Design programme during 2004/05. The projects aim is to produce a simple technology demonstration satellite that can operate as a test bench for Micro System Technology (MST). The main objective of the payload section of the project was to develop the interface specification that was produced in the previous 2001/02 project. The project also intended to identify suitable payloads for the first MUSTANG 0 mission, along with an operational description of how the payloads would function. The design of the payload interface was based around the concept that the satellite should be able to operate different payload configurations, with only minor alteration to the baseline satellite. The payloads themselves have been chosen due to there suitability to nanosatellite missions, whilst the operational methods that are developed arise from the need to test each of the payloads with an efficient use of the resources available. From the interface that has evolved during the project, the interface specification document found in appendix B has been modified so that it is compatible with the design of MUSTANG 0. A generic interface mounting plate was developed to attach each of the four payloads to the structure of the satellite. This evolution in the interface design will lead to increased inter-changeability of future payloads. The interface that has evolved during the project is able to integrate the current payload options with the resources available on the MUSTANG satellite. To develop the interface further, the separate payloads should be individually integrated with the satellite using the interface. Further research is needed on each of the payloads to confirm the conditions and operational methods of there deployment can still be achieved

D.1.2 Introduction

The task of developing the interface document that was already in place for the previous MUSTANG design was an ongoing process which took place over the lifetime of the project. The mechanical interface was developed to create a system in which future payloads can be inter-changed with little alteration of the baseline satellite. The candidate payload's specifications were scrutinised to make sure that the interface could be used on as many payloads as possible, without sacrificing the robustness of the interface.

The operation procedure of each of the four payloads to be used on MUSTANG was developed to inconsistencies that occurred between the satellites resources and the payloads requirements.

During the project the top level requirements for candidate payloads was modified, to include space science payloads, as well as technology demonstrating payloads.

D.1.3 Payload section

The payload section of the MUSTANG satellite is situated in the bottom 9.5 cm of the octagonal structure of the satellite. The compartment has been split up

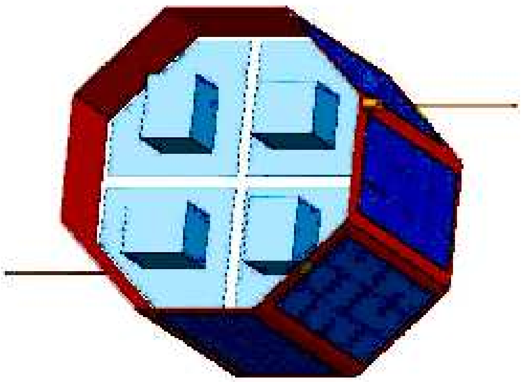


Figure D.1: The four payload interface plates, and representative payloads can be seen in blue

	Payload testing							Other modes	Safe mode
Continuous use	Y	Y	Y	Y	Y	Y	Y	Y	
Occasional use 1		Y	Y						
Occasional use 2				Y	Y				
Occasional use 3						Y	Y		

Table D.2: The proposed operation timeline of one orbit.

into four separate sections that will each hold one payload. The total mass of the payload compartment is 1 kg, giving each of the payloads 250g. This 250g will include the generic interface that will attach the payload to the satellite

The interface mounting plate that is used to attach the payload to the satellite came about though the need to make the alterations needed to change the payloads on the satellite as small as possible. The four interface plates, along with boxes representing payloads can be seen in figure D.1.

The centre of mass of the whole payload compartment will be central in line with the centre of the octagon. Again this standardisation of the centre of mass has been done so that the payloads can be changed without any major redesign of the baseline satellite

D.1.4 Payload operations

Before the operation modes and procedure could be developed, the candidate payload must be classified by their power use. Payloads can either be continuous use payloads, or occasional use payloads.

Continuous use payloads draw power from the satellite at all times during the mission of the satellite except when the satellite is in safe mode. The occasional use payloads only draw power from the satellite during the payload testing mode, and even then the occasional use payloads will take it in turn to operate. Using this procedure will limit the amount of payloads that are operating at one time. Table D.2 shows an example satellite orbit with a payload testing mode, other modes and a safe mode.

The four payloads that are being operated on the first mission are:

CMOS Active Pixel Camera

This payload is a technology demonstration payload, that will space qualify the camera. It will also take images of the launcher and the de-orbit device for PR purposes

Aerobrake De-Orbit Device

The de-orbit device is also a technology demonstration payload. The device will de-orbit the device from a LEO

Radiation Dosimeter

This payload is the only space science payload on the first mission. It will measure the radiation levels in the space environment.

Mobile phone transmitter

Our last payload on the first mission is a technology demonstration payload that will test the concept of using transponders taken from commercial of the shelf (COTS) technology i.e. mobile phone components, in a small transmitter.

D.1.5 Conclusion

The development of the interface specification document form the previous MUSTANG project has been carried out so that the design modifications that have taken place during the 2004/2005 GDP are accounted for in the interface document. The document is designed to be a complete guideline to the payload to satellite interface. It is possible for candidate payloads to be compared against the information provided in the interface specification document, and so determine weather or not the payload is suitable to operate on MUSTANG 0. The document has had two main updates from its original creation during the 2001/02 DGP. The main area in which the interface specification has been updated is the mechanical interface. A design for an interface plate has been developed so that the payloads can the interchanges with less alteration of the main design than was possible with the previous interface. The power regulation system has also been updated. With more voltage levels available to payloads. The advance of the operational modes and operational structure of the payloads now means that perspective payloads can be classified not only by there mass, and power requirements, but by there operational use. The ongoing work in the development of the payloads for the first mission means that the operation structure for the CMOS camera and de-orbit device have now been completed.

The candidate payloads that have been selected for deployment on MUSTANG 0 have had to adhere to the guidelines set out in the interface document, this was not always achievable. The conflicts that arouse between the payloads requirements and the satellites resources were consolidated with the development of an operational procedure that overcame the differences in the needs of the payload and the design limitations of the satellite. This method of designing the operational procedure of a payload to change the requirements of the recourses of the satellite should be considered at all times when considering a future payload.

Even though the payloads have been chosen due to there adherence to the interface guideline, and in many cases the interface designed around all of the candidate payloads, there still remain some unresolved interface issues

D.1.6 Further Work

The interface is still far from complete. Further development is needed in the thermal and data interfaces sections. When these sections have been completed, each of the candidate payloads should be integrated to the baseline satellite using the interface guidelines set out in the interface specification document. The success or failure of the integration will lead to adjustments and/or modifications to the interface for the current design of MUSTANG 0.
However due to the constant development of the MUSTNAG design, the interface will have to adapt to the new design features of future MUSTANG design. This means that the interface document cannot be completed until a critical design of MUSTANG is approved.

D.1.7 References

Cranfield university. Project Information Document. Group Design Project report for MSc in Astronautics and Space Engineering, Cranfield University, 2002.

Ashman, M., Payload Interface. Group Design Project report for MSc in Astronautics and Space Engineering, Cranfield University, 2002.

Presley S.P.., The Spacecraft-to-payload Interface Guideline (SPIG). The Aerospace Corporation, AIAA.1995

Crerar, R., Payload Structure. Group Design Project report for MSc in Astronautics and Space Engineering, Cranfield University, 2005

D.2 Attitude and Orbit Determination and Control (Ross Burgon)

The MUSTANG0 nanosatellite project is a Group Design Project (GDP) carried out by students on the Astronautics and Space Engineering MSc course at Cranfield University in 2004/05. The MUSTANG0 nanosatellite is primarily a technology demonstrator for Micro Systems Technology (MST) and Micro Electro-mechanical Systems (MEMS) payloads. The mission constraints for MUSTANG0 are detailed below:

1. MUSTANG0 must remain a low mass satellite (10kg max)
2. MUSTANG0 must be a low cost satellite befitting of its University budget
3. MUSTANG0 should be a generic platform able to offer its services to a wide variety payloads in a wide variety of orbits without the need for drastic mission-by-mission redesign

This report is on the subject of Attitude and Orbit Determination and Control. Attitude determination and control is concerned with how the satellite orientates itself in the orbit and controlling this orientation. This report describes the rationale behind the selection of the Attitude and Orbit Control System (AOCS) for this mission and the selection, sizing and design of the sensors and control actuators chosen. The report follows a design scheme by Eterno, 1999, pp. 356.

D.2.1 AOCS: Requirements and Selection

Selection and sizing of the hardware required to perform the tasks of the AOCS depends on the mission requirements, payload requirements, sub-system requirements and the disturbance environment likely to affect the nanosatellite.

Attitude Control System (ACS)

The MUSTANG0 ACS needs to provide attitude control for the following reasons:

- The camera payload needs to be pointing at the Earth for it to take an image of it. The field of view of the camera is unknown at this time but it is assumed that a pointing accuracy of less than 5^o is required.
- MUSTANG0 should demonstrate the ability of the spacecraft bus to be available to all payloads in all orbits without bus re-design. This means a control system needs to be flown to demonstrate to future payloads the control accuracy MUSTANG missions can obtain. There is no defined pointing accuracy for this requirement so an arbitrary value of 0.1^o is selected as a guideline.

Having analysed all available control options a 3-axis reaction wheel control system was chosen with magnetorquers for momentum dumping. This allows MUSTANG0 to verify its control accuracy in 3-axes with a reaction wheel assembly (RWA) and in 2-axes with magnetorquers should the RWA fail.

Attitude Determination System (ADS)

The MUSTANG0 ADS is required for the following reasons:

- As active control measures have been selected for the ACS so accurate knowledge of the attitude will be vital to the successful operation of the control algorithms.
- As the first of many potential missions, it is important to analyse how the disturbance environment affects the attitude of MUSTANG0 in a real orbit setting. This will enable designers of future MUSTANG missions to model their ACS on known conditions. Since future missions may well be testing MEMS/MST sensors and actuators this information will give future developers a valuable insight into how MUSTANG has previously responded to such disturbances.

After examining all available options for attitude determination hardware it was decided to choose sun sensors and an Inertial Measuring Unit (IMU) to carry the ADS requirements. The Nanotechnology MSc, for their GDP, designed the sun sensors at Cranfield University. Six will be needed to provide full 4? steradian coverage of the sky. Their mass properties are tiny and they require no power thus making them a cost effective way of determining MUSTANG0's attitude. The nanotechnology group believes their sun sensors may also be able to operate as horizon sensors, thus adding to their value on board.

The IMU selected is the MT9-B designed by Xsens. With on-board accelerometers, rate of turn sensors and a magnetometer the MT9-B is able to provide drift-less 3D orientation with an angular resolution of 0.05^o, accuracy of $<1^o$ and a sample frequency of up to 512Hz. The information from the MT9-B will be used to reinforce the attitude information from the sun sensors, provide coarse attitude information during eclipse periods and give magnetic field information prior to use of the magnetorquers. As a unit developed for terrestrial use the MT9-B will have to modified and tested for space use.

Orbit Determination and Control

Determination of the orbit of MUSTANG0 will be primarily achieved through ground station radio frequency (RF) ranging during communications passes. However since the nanosatellite will only be communicating with one ground station there will be considerable periods of time where information to extrapolate the orbit is unavailable. Therefore as a back up it was decided to place a GPS receiver onboard. The data from the GPS would be stored and sent to the ground station during a communications pass. This allows much more orbit data to be processed by the ground station to predict the future orbit of the nanosatellite. Space qualified GPS receivers are very expensive so a space adaptation of a terrestrial model needs to be studied.

Control of the orbits of satellites is primarily achieved through the use of thrusters. MUSTANG0 cannot afford to include thrusters (in their present form) as part of the nanosatellite bus. For future missions, MST thruster banks could become payloads, but they are not necessary for MUSTANG0. This means there will be no orbit control other than the de-orbit device, the deployment of which signals the beginning of the end of the mission.

$\mu = 5.9 \times 10^{-3}$ A m^2	r = 2.3 cm	P = 0.59 W	m = 9 g	I = 99 mA
d = 0.5 mm	N = 36	L = 5.14 m	V = 6.0 V	R = 60.8 Ω

Table D.3: Trade-off results of magnetorquer sizing for disturbance torque balancing in a 200 km GTO (equatorial orbit)

D.2.2 Control Hardware

The cost of space qualified control hardware prohibits its use for MUSTANG0. It was decided that the RWA and magnetorquers could be manufactured, assembled and tested at Cranfield University. This also has advantages as the components are designed specifically for MUSTANG and not the 'closest fit' found buying ready-made components. The control hardware was designed taking into account the maximum disturbance torque the nanosatellite is likely to experience and the amount of angular momentum the nanosatellite is expected to store.

Reaction Wheel Assembly

Sizing of the reaction wheel assembly centred on the angular momentum storage capabilities. It was calculated that a reaction wheel with mass and size constrained (approx. 50 g mass and 15 mm radius) to fit MUSTANG0 could hold 0.025 N.m.s of angular momentum spinning at 40000 rpm. This corresponded to an accumulation of one-day's angular momentum in a 600 km circular LEO. In any orbit below this height the aerodynamic disturbance torque gets larger and to balance this torque requires larger or faster reaction wheels. The aerodynamic disturbance torque was calculated using the distance from the centre of pressure to the centre of mass as 5 cm. Reducing this value to 1 mm allows all orbits to 200km to be included but this is near impossible accuracy to achieve. This leads to a limiting orbit height of 600km for 3-axis reaction wheel control. Orbits below this height will need to use 2-axis magnetorquer stability instead.

To achieve the angular momentum storage requirements a flywheel of mass 50.31 g and radius 15 mm will be mounted on a Maxon Motors Ltd EC 6 brushless DC micromotor capable of 40000 rpm. The reaction wheel will be controlled by a Maxon Motors Ltd 1-Q-EC Amplifier DEC 24/1 controller capable of giving the wheel an accuracy of 0.35^o in either direction.

Magnetorquers

It was found that sizing the magnetorquers for disturbance torque balancing or momentum dumping made little difference to the mass and power required. They were therefore sized for disturbance torque balancing in a 200 km GTO. This orbit exhibited the largest single disturbance torque MUSTANG0 was likely to experience. A magnetorquer coil of properties seen in Table D.3 can produce a magnetic moment of 5.9×10^{-3} A m^2 ($\mu = nIA_x = nI\pi r^2$) relative to the 14.2 A m^2 magnetic dipole moment required to balance this torque [*the magnetorquer coil design needs to be checked*]. With control electronics similar to those used for the RWA, 1^o accuracy in 2 axes should be achievable.

D.2.3 Future Work Required

The AOCS designed in this report will is far from being realized and much work is still required before a flight system can be developed. This is briefly summarised below:

1. The reaction wheel assembly needs to be manufactured, assembled and tested including design of the housing and mounting structure.

2. The magnetorquers need to be manufactured, assembled and tested including design of the housing and mounting structure.

3. The sun sensors, IMU and GPS need to be procured, modified and tested for space use.

4. The AOCS control law and software needs to be written and integrated into the MUSTANG0 bus software.

D.2.4 References

Eterno, John S. Attitude determination and control. IN: *Space mission analysis and design.* 3^{rd} ed. Edited by Wertz, James R. and Larson, Wiley J. Dordrecht, The Netherlands: Kluwer Academic Publishers Group, 1999.

D.3 Mustang0 System Engineering (Damian Cambronero)

This section provides an executive summary of the student's report. Detailed descriptions are provided in chapters 2 and 3 of the full student report.

This report is intended to provide the description the work of the author along 5 months in the intricate task of system engineering-interfaces in Mustang0 nanosatellite project.

The aim of the author has been to understand and integrate all subsystems in one system; this is the system of system engineering-interfaces. This task has been divided in various steps.

The first step was to define the requirements of the mission as Wertz and Larson [15] proposed chapter 4. For this project 3 main requirements have been defined as it has been provided in this report by chapter 1 table 2, as well as several derived requirements as table 3 chapter 1 shows.

The second step was to create a baseline of the project, table 1 in chapter 1.

The next step has been to specify the interfaces of this project in detailed as Wertz and Larson [15] in chapter 4. As system engineering-interfaces the responsibility of the author was to define precisely the interfaces of this project.Mustang0 which has mainly 2 interfaces, namely: internal and external as it is explained in this report in chapter 2

External interfaces are: space environment and ground station

Internal are essentially: power, data and thermal/mechanical as T. Bowling ref [2] explains (page 30).

Finally in order to integrate all subsystems and interfaces in one system compatible with all subsystems, it was designed a system model (SM) with the purpose of managing all parameters of the satellite to obtain critical interfaces, risks of the mission and optimization of the satellite as whole.As well as, to help the selection of the orbit for the satellite as a system and evaluation of the lifetime of the mission.

D.3.1 Requirements

The requirements of the mission are categorised in primary and derived.

Primary requirements are:

1. 10 kg maximum (type of nanosatellite), low cost;
2. structure must be manufactured in Cranfield;
3. nanosatellite must use MST for space applications.

Derived requirements are:

1. Must ability to operate in any available orbits
2. Must meet any launch vehicle requirements, both mechanical and electrical
3. Must use only one ground station
4. Lifetime of the mission

Payload	4 different payload - Mobile phone - Radiation dosimeter - Camera - Deorbit device
Structure	Carbon (high strength) for the external panels, sandwich panels for bulkheads, and aluminium for the internal panels
Communications	UHF band
Power	Solar cells with recharged batteries
AOCS	3 axes, (two possibilities): - Magnetorquers (reduce costs) - Reaction wheels

Table D.4: Summary of the Mustang0 baseline design

5. Must provide enough memory for operations
6. Must provide enough data rate
7. Must survive to space radiation
8. Must provide enough power
9. Must stay within the required temperature range.
10. Structure external shape and size (previous mustang project)

As result of the primary and derived requirements is readily to define the base line of the nanosatellite , this baseline is:

D.3.2 Interfaces

External

The author has considered two main important external interfaces, such as radiation and ground station.

An exhaustive study of radiation was undertaken with the integration in a dose package of several radiation models available in ESA website in order to rapid and accurate calculation of radiation. These models are AE8, AP8 NASA models for trapped particles and JPL model for solar protons and SHIELDOSE model.The conclusion of this is a dose package tool with the input of orbit and lifetime, the output is the total dose in depth-dose curves (dose vs. shielding thickness) for many orbits of choice, of several varying altitudes, inclinations, and mission lengths.

The conclusions for this mission Mustang0 are:

1. Missions longer than 3 years and with high altitudes, the level of radiation is two order of magnitude (without shielding) higher than the requirement of radiation in our mission processor (1 Mrad) and camera (10 Mrad).
2. Polar orbits in LEO the level of radiation increase dramatically nearly to the radiation requirement.

3. In terms of shielding , it is possible to protect the satellite against the radiation with shielding, in contrast the disadvantage of increase the mass Mustang0 has been decided to use various ground stations as well as portable ground station. Subsequently the best method of communication between satellite and ground has been analysed.

Internal

The author of this report has established the main interfaces between all subsystems such as power, data and thermal/mechanical. After that the author in the role of system engineering in charged of interfaces, the author has promoted interfaces meetings, such as power interfaces, data interfaces and thermal/mechanical interfaces.

The conclusions of these meetings have been the starting for defining the global interfaces in Mustang 0.

Further this, the author has the on-going design systems and the interfaces of subsystems.

D.3.3 System model

The subsystems design on-going and the interfaces clearly defined, it is essential to develop some tool in order to manage all parameters as well as to study critical interfaces and risks of the mission.The selected tool was a spreadsheet of excel ,since it is powerful and easy to manage a lot of data. This spreadsheet is divided in several sheets such as: mission, component, subsystems (AOCS, power, communications,payload,thermal control, structure,ground),cost model (mass breakdown,power breakdown,cost breakdown),iterations sheet.

The conclusions for Mustang0 project:

- Critical interfaces
  - Low data rate as result of lower power
  - Low data rate with low power implies increases the data storage on board
  - Power available as a function of the solar cell efficiency and satellite size
- Risks of the mission
  - Reduction of power generation in 20%
  - Failure of processor
- Selection of the orbits
  - LEO no polar orbits with radiation analisis
  - LEO and MEO in polar and no polar orbits
- Mission lifetime less than 1 year

D.4 Mustang 0: Structure and Configuration (Robyn Crerar)

The MUSTANG 0 project is a multi-university project run at Cranfield University in association with the University of Southampton and EADS Astrium. The project is an ongoing study to design and at some point in the future, hopefully produce a nanosatellite to test MST in space. The structures group was given the task of determining the configuration of the MUSTANG 0 satellite and analysing it in terms of its structural and thermal integrity. Axel-Raphael Demure performed the thermal analysis and the author determined the configuration and preliminary structural analysis.

D.4.1 Structural Components

The satellite consists of three main structural components:

1. A CFRP (M55J/EX1515) tube provided courtesy of EADS Astrium
2. Two Honeycomb sandwich panel (Hexlite 110) bulkheads
3. A light Alloy (Al 7075-T6) internal panel

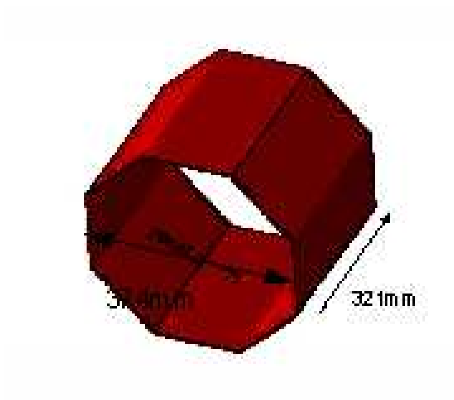


Figure D.2: The CFRP tube with dimensions marked

The dimensions of the CFRP tube were set at the beginning of the project and hence so were those of the bulkheads. The design of the internal panel was chosen from an analysis of several possible configurations due to its large surface area and the flexibility it offers in the positioning of the payloads.

External Configuration

The design of the external configuration was mainly controlled by the requirements of the power work package (Kristina Larfars and Philip Soeberg). MUSTANG 0 is a very small satellite with no extendable solar arrays, therefore in order to generate sufficient power for normal operation it was imperative that the surface area dedicated to solar cells was maximised. This had several affects on the external configuration.

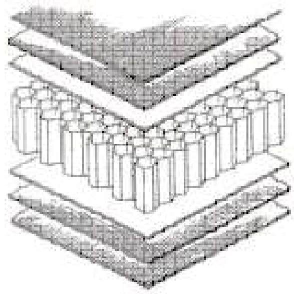


Figure D.3: Representation of the honeycomb panel used for the bulkheads

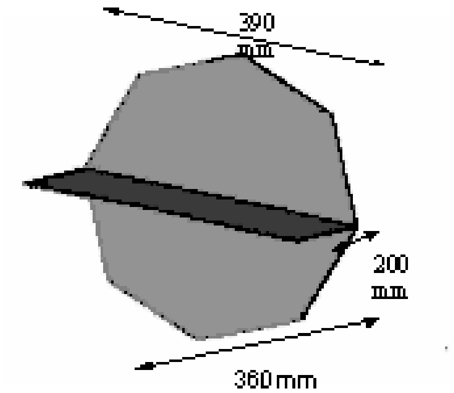


Figure D.4: Final design of the light alloy internal panel, with dimensions marked

- The launcher attachment ring had to be moved from its initially intended position on the top bulkhead (Fig. D.5) to the bottom bulkhead (Fig. D.7), since the top bulkhead is expected to predominantly be towards the sun and therefore receives the most solar flux. With the attachment ring on this side there were inadequate solar cells to produce the power necessary for normal operation of MUSTANG 0
- The antenna were placed on the side panels, since there was not enough space for one on the bottom bulkhead once the de-orbit device and attachment ring had been positioned. They are omi-directional antenna so still provide the necessary coverage
- There are six sun sensors arranged evenly around the satellite to provide attitude determination
- There are three external payload slots on the lower bulkhead, rather than the intended four, designed to correlate with the internal payload areas. This was the result of the solar cells being networked in series of three and the need to avoid shadowing by the de-orbit device.

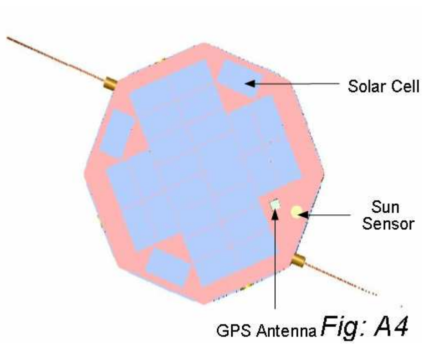


Figure D.5: Top Bulkhead

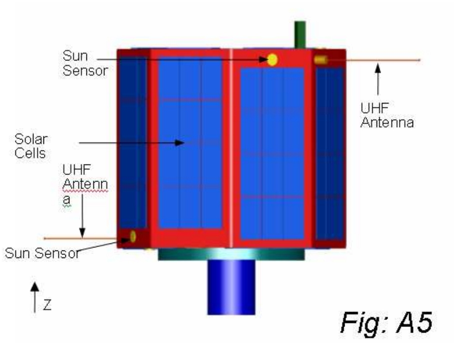


Figure D.6: Sides

D.4.2 Internal Configuration

The design of the internal configuration was mainly determined by the need to maintain the COM as near to the centre of the satellite as possible. Specific points worth mentioning include:

- The payloads were dedicated the entire lower surface of the horizontal panel in order to give flexibility to their placement and also to allow easy interchange between payloads without affecting the rest of the configuration
- The magnetorquers (pink) are mounted on the upper side of the horizontal panel to distance them from most wiring since they are sensitive to magnetic interference
- For the reaction wheel assembly (RWA) to work the COM and COP but be coincident to within 50mm in any axis.

Structural Properties

The COM, COP and Inertial properties were calculated with the slight simplification of modelling the components as constant density boxes (tables D.5 and D.6). The results are presented below and comply with the launch requirements

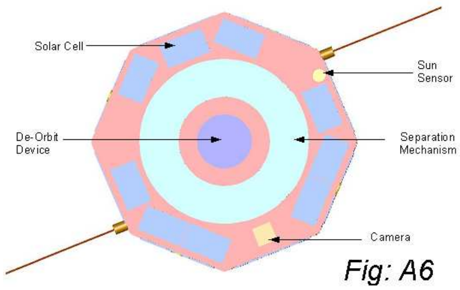


Figure D.7: Bottom Bulkhead, Components labelled

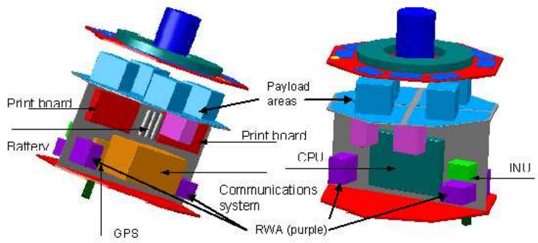


Figure D.8: I-DEAS drawing of the Internal configuration of MUSTANG 0

that state that the COM must be within 5mm in x and y and 450mm in z of the satellite centre, and that the moment of inertia (I) must be <20kg m^2.

Cost and mass budgets for the satellite are also presented, (Table D.7)

Fastenings

The fastenings were developed from the 2001/02 designs proposed by Ellie Allouis. Figure D.9 shows the brackets for attaching the bulkheads. They are secured to the shell with 5mm Titanium dowels and the bulkheads are held in place by two M5 screws , which are fastened into threaded holes.

Figure D.10 shows the slot brackets used to support the internal panel. The vertical panel will be supported by the slot and the horizontal section shall rest against the solid lower end of the bracket were it shall be secured using two M5 screws as for the bulkhead attachment. The corners of the horizontal panel will be supported by brackets similar to those in figure A8.

D.4.3 Summary

The configuration and structure satisfy the baseline constraints on the satellite in terms of the configuration, COM, COP and inertial requirements. A prelim-

	X / mm	Y / mm	Z / mm
COM	0.037	0.057	12.00
COP	0.00	0.00	0.023

Table D.5: The center of mass (COM) and centre of pressure (COP) values for MUSTANG0 with respect to the centre of the CFRP tube. *worst case values, alter depending on orientation

Ixx = 0.178		
Ixy = -0.00834	Iyy = 0.176	
Ixz = 0.00405	Iyz = -0.00158	Izz = 0.137

Table D.6: Moments of inertia in units of kg m^2

	mass / g	cost / £
CFRP tube	1200	5000
Internal panel	1110	40*
Bulkheads	420	200
Fastenings	700	200?
Total	3420	5540

Table D.7: Cost and mass budgets for the structure of MUSTANG 0

inary FE model has been designed but due to computer difficulties no results have as yet been obtained. Future work should consist primarily of development of the FE model. A detailed analysis of the fastenings and wiring must also be undertaken.

Figure D.9: Fastening view

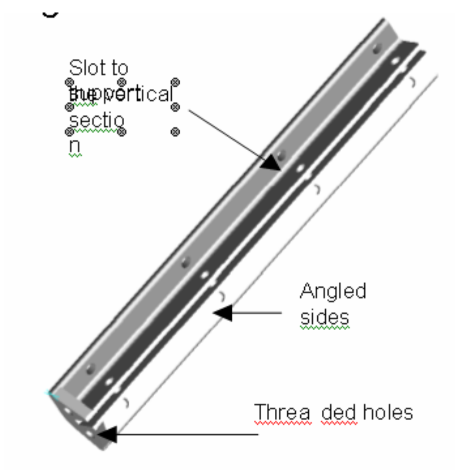


Figure D.10: Guide rail

D.5 MUSTANG0: Thermal Analysis and Design (Axel Demeure)

The submitted thesis appears to have some confusion between what are claimed to be the worst hot and cold cases. The confusion is probably due to typographical errors and the main statements in this executive summary have been corrected so that the worst hot case is sunlit LEO (external heat input from solar radiation, reflected light from Earth plus Earth thermal) and the worst cold case will be in eclipse at GEO radius (only Earth infrared external heat input).

D.5.1 Abstract

The focus of this paper is to present the Thermal analysis and the Thermal Control System design for the MUSTANG0 satellite. The Thermal analysis was performed to define the orbits leading to the Worst Cold Case and to the Worst Hot Case in terms of thermal environments. To achieve this a basic model in an Excel spreadsheet was done. Then a non-linear model of the spacecraft orbiting the Earth was implemented using the calculation software Matlab. The objective of the thermal design was then to define a coherent thermal control system strategy for the spacecraft in order to ensure it to cope with any orbit between the worst cold case orbit (450 [km] LEO) and the worst hot case orbit (36000 [km] GEO). A functional thermal control strategy was finally defined.

D.5.2 Introduction

The Thermal Control System of a satellite is one of the most important part of it. Indeed, without a functional thermal control strategy, it is very likely that some component inside the spacecraft may not work properly. However, before starting the thermal Design in itself, it is very important to have a good understanding about thermal environment. This is why we first started with a Thermal Analysis.

D.5.3 Aims

There were several purposes to this work, but the two most important ones were certainly firstly to define the worse orbits in term of thermal environment and secondly to design a thermal control system that ensure all spacecraft's component temperatures to stay within their own safety range of temperature.

D.5.4 Thermal Analysis

A basic model implemented in an Excel Spreadsheet gave us the following qualitative results:

- Worst Hot Case orbit = 450 [km] LEO
- Worst Cold Case orbit = 36000 [km] GEO

The more complex Matlab model was used with a wide range of orbit. The orbits tested are summarized in Table D.8.

Altitude [km]	450, 800, 1500, 4000, 8000, 20000, 36000
Inclination [$^\circ$]	0, 15, 30, 45, 60, 75, 90
Declination of ascending node [$^\circ$]	0, 30, 60, 90, 120, 150

Table D.8: Tested orbits

This broad test was perfectly confirming the first results as here is what we found

- Worst Hot Case orbit = 450 [km] LEO - $i = 45^\circ$ - $\omega = 90^\circ$
- Worst Cold Case orbit = 36000 [km] GEO - $i = 0^\circ$

D.5.5 Thermal Design

An almost complete thermal model of the spacecraft was created with the software package Ideas-TMG.

The model was tested first without any thermal control strategy. Table D.9 shows the results obtained.

Component	Safety Range		Worst Cold Case		Worst Hot Case	
	T_{min} [$^\circ$ C]	T_{max} [$^\circ$ C]	T_{min} [$^\circ$ C]	T_{max} [$^\circ$ C]	T_{min} [$^\circ$ C]	T_{max} [$^\circ$ C]
Payloads	0	40	-24	36	-11	49
CPU	-25	85	-18	48	-5	57
Batteries	0	20	-21	22	-12	34
PCU	-20	60	-18	48	-2	58
Reaction wheels	-20	100	-27	21	-18	34
Communications	-20	60	-27	29	-12	45
Structure	-100	100	-51	56	-20	75

Table D.9: Component temperature ranges without thermal control strategy

As you can see, almost all spacecraft's components are going out their safety range of temperature. It was thus compulsory for us to design a Thermal Control System. However, due to the high requirements in term of mass and then in term of power, it was not possible for us to use Active Thermal Control Systems as they are often heavy and large power consuming.

We achieved a lot of simulation with Ideas-TMG and finally we founded a functional thermal control system. It consists in applying a white thermal coating on the inside part of the spacecraft in order to minimize radiative heat transfers inside the satellite, and in multi-layer insulation blankets placed on the Batteries and on the CPU.

Table D.10 presents the calculated component temperatures using this thermal control strategy.

As we can easily see, there are no components whose temperature is going out its safety range.

D.5.6 Conclusion

Although a lot of work has still to be performed in this Work Package, we can see that we are on the good way to finalize the complete thermal control system.

Component	Safety Range		Worst Cold Case		Worst Hot Case	
	T_{min} [$^\circ C$]	T_{max} [$^\circ C$]	T_{min} [$^\circ C$]	T_{max} [$^\circ C$]	T_{min} [$^\circ C$]	T_{max} [$^\circ C$]
Payloads	0	40	2	22	12	38
CPU	-25	85	5	45	14	61
Batteries	0	20	1	12	5	19
PCU	-20	60	-5	24	7	42
Reaction wheels	-20	100	-10	17	18	31
Communications	-20	60	1	28	16	36
Structure	-100	100	-47	50	-9	48

Table D.10: Component temperature ranges with thermal control strategy

However, it would be very interesting in the future to increase the complexity of the Ideas-TMG software in order to take more details into account.

D.6 MUSTANG 0: Data and Software Onboard the spacecraft (Diependaele)

Mathieu Diependaele
Space Research Centre, School of Engineering, Cranfield University

D.6.1 Abstract

As a member of the Astronautics and Space Engineering course for the academic year 2004/2005 the requirement was to take active involvement in the Group Design Project MUSTANG 0. This project was a continuation of the preliminary study already carried out by the previous year's students. The document, which this summary supports, presents the steps taken in the data and software onboard MUSTANG 0. The data and software analysis involved both hardware research and software development. The considerations in the hardware design included; low mass, low cost and low power.

D.6.2 Introduction

The Report tries to be as complete as possible and assumes that the reader is entering the course with little or no previous OBDH experience.

The outline is simple and logical. Subsequent to a brief introductory overview of Mustang0, the report is divided into 2 parts.

Following the basic introductory material, the report consists of two sections, although they are not explicitly separated. The first Section, Chapters 2, deals primarily with the literature, fault tolerance and the argument towards a Mustang0 computer Environment. The second section, chapters 3, deals with the software part. The breakdown is as follows:

Chapter 2, "Environment" outlines description of the finer points to note about the selection of Mustang0 Computer unit Hardware (Microprocessor, additional memory)
The 2^{nd} part of that chapter will study the data bus in general and with a lot of precision on the I2C bus. At the end of that section the reader will understand about communication via the bus and the different problems that can occur during the communication.

Chapter 3, "Software" takes a look at the feasibility of the software. In that part, the reader will realise the logical step, the requirements before coding software. A demonstration of the software will end that part.

Chapter 4, "Conclusion", concludes the formal part of the report

D.6.3 Environment

In this chapter, a study of hardware was made. It concerns both the CPU hardware with the microprocessor and data storage than the communication hardware with the data bus. This latter is a serial data bus manufactured by Philips semi conductors and presents a lot of special characteristics.

Microprocessor

The Microprocessor has to be tested for a period of 10 or 15 years so as to get the label Space qualified. It is obvious that such a processor must resist to the hostile environment of space (radiation, temperature).In other words; there is always a delay between the technology market and the technology applied in space. By instance, on the market we can find laptops with a Pentium processor with a frequency of 3.2 GHz whereas in space, the quicker speed is around 100MHz. It appears that all the processors do not have the same properties. To meet the requirements of our mission, it seems that the PowerPC 603e is more adequate. Indeed, this processor is quite low cost (comparing with the other processors).

According to Robert M.Manning (1993), despite of the high marginal cost per kilogram and cost per watt ,spacecraft computers are often characterized as having poor performance with respect of those key drivers. The new demands made by the very small, low cost spacecraft concept invite a re-evaluation of the problems and solutions that traditional spacecraft designers have faced.

The performance can be found on commercial microprocessor. However, the manufacturers have to concentrate their efforts for improving the radiation protection and fault tolerance. Therefore, for MUSTANG 0, we will opt for existing solution and space qualified components.

Data Storage

In every communication system, we will transmit data. The most critical operation in terms of data storage would be to store the raw image taken by the camera of 6.2 Mbytes. We have to think about worst cases of no communication with the ground station. Therefore if we can not download the image file during various orbits, we will loose data. In order to avoid that, we will need further memory. In the market, it exist 2 solutions to store the data:

1. Hard memory tape
2. Memory card

It appears that all memory hardware do not have the same properties. To meet the requirements of our mission, it seems that the memory Card NvCpi of 256 Megabytes is more adequate. Indeed, this memory card is quite low cost (comparing with the other memory solutions), low mass and low power. An alternative was thought for switching off this additional memory for saving power during critical modes of operations.

D.6.4 Data bus

This part of the report deals with the understanding of data bus in general. What is the difference between a serial and a parallel data bus? In addition, the logic of the selected I2C bus is explained. There are various steps for transmitting data. It is under logic of master/slave. The master initiate the condition for transmission and the slave collect the data and execute the order of the master. The master can be seen as a transmitter of orders and the slave as a receiver in a simple way. The fault tolerance as well as the future devices to implement will be part of future recommendations

D.6.5 Software

This year, the author managed to implement demonstration software for having an overview of the data handling. The user's manual is given in the report. The limitation of the software is due to a lack of data. Therefore the author recommends for further work a deep investigation in data handling for every subsystem. Before coding, a study of treatment (functional point of view) and data has been made by the author. Architecture was also designed. The code is given in appendix.

D.6.6 Conclusions

During that project a software was achieved as well as a component study for the data handling. After looking for various components, the author came out with a selection of microprocessors, data handling and data bus that will comply with the requirements of MUSTANG 0 project. The reader has to bear in mind that, according to the hostile environment in space, all the commercial and low cost components can not be used for that mission. The author believes that in the future commercial components can be applied in space technology and therefore reduce the cost of the overall mission significatively.

The Mustang 0 project is very interesting for MSc students to test their knowledge and apply them in a real space related project. The architecture of work in group gives also a good experience of what could be the work in a team with all the advantages and drawbacks that implies. A real presentation in front of Space companies is also a good training for future project presentation. I therefore recommend to carry on that project with may be more project management so as not losing time by taking decisions.

D.6.7 References

Manning R.M, (1993),"Low cost spacecraft computers: Oxymoron or Future Trend?" In: *Guidance and Control Conference 1993",* Keystone, Colorado, 6-10 February 1993 Vol.81 Advances in the Astronautical Sciences

Philips Semiconductors. (2000). "The I2C Bus Specification", Version 2.1, January 2000.(pdf document).

`http://www.semiconductors.philips.com/acrobat_download/literature/9398/39340011.pdf` (Accessed March 2005).

Larson, Wiley.J. and Wertz, James.R., (1992). Space Mission Analysis and Design, 2$^{\text{nd}}$ ed. Space Technology Series. Microcosm Inc and Kluwer Academic Publishers. 1-881883-01-9

D.7 Mustang0: System Engineering (Bertrand Dufaÿ)

SCHOOL OF ENGINEERING
MSc in ASTRONAUTICS AND SPACE ENGINEERING
GROUP DESIGN PROJECT REPORT EXECUTIVE SUMMARY

The objective of this project was "*to design a nanosatellite mission (using available hardware and a level of technology appropriate to a university nanosatellite) which will provide suitable benefits/enablers for an on-going programme of space MST*".

Based on this statement the main requirements are: to design a satellite which mass is around 10 kg without developing any new technology. This satellite is a university satellite and then this is a low-cost mission. Mustang 0 will be also a technology demonstrator for microsystem technology. The mission will not be seen and designed as a "stand-alone" mission.

D.7.1 Timeline

The Group Design Project was divided into two parts, phase A and phase B. At the end of each part, a review was made to synthesize the work done. The Preliminary Design Review (PDR) was at the end of phase A whereas the Critical Design Review was at the end of phase B.

The design of Mustang 0 was first made for a particular orbit to simplify the calculation. This first orbit was LEO 800 km. This orbit was chosen from a trade-study from different orbits. After this stage, the design was adapted to be used in the maximum number of orbits.

D.7.2 Mass budget

The total mass of Mustang 0 is 8.3 kg and then this validates the mass requirement that impose a maximal mass around 10 kg. Moreover, there is a good margin of 1.7 kg for the addition to the design of things such as the shield against debris and the radiations protection. However, based on the repartition of the mass between the different subsystems, the best way to reduce the mass would be to reduce the structural mass of Mustang 0 if it is possible. Yet this is not necessary as there are enough mass margins but it could be a good way for future designs.

D.7.3 Power budget

Power was a critical system during the design of the satellite as the power consumption was too high compared with the power available from the solar panel. This problem was solved by dividing the modes of the satellite into several sub-modes in which some components are off to reduce the power consumption.

The power consumption can again be reduced by switching off the secondary memory in some cases so as to save some power. This would be decided by the future team which will work on Mustang 0.

	Safe	Eclipse	Normal	Comms	Payload	AOCS
Power / W	10.93	15.40	15.40	19.03	15.75	16.54

Table D.11: Power consumption for the different modes

Payload	Mobile phone SAR Camera De-orbit device
Structure	Carbon (high strength), external panels Sandwich panels, bulkheads Aluminium, internal panels
Communications	UHF band
Power	Triple junction solar cells Li-ion battery
AOCS	3 axes (two possibilities) magnetorquers (low cost) wheels (better accuracy)

Table D.12: Baseline of the Mustang 0(PDR) 06.12.04

D.7.4 Cost budget

The total cost of the platform is around £75,700 and the satellite is around £80,200. These values are under the maximal cost of a University nanosatellite which is estimated to £100,000 maximum. There is also some margin for the future work and more complete designs of the satellite.

This cost budget and estimations could be used later to create historical databases about nanosatellites and then define general relationships to make the cost estimations easier for future nanosatellite missions.

D.7.5 Baseline

At the end of the first period, a Preliminary Design Review was made to define the baseline of Mustang 0. The methodology used to obtain this baseline was a step by step one. It started with all the designs possible and this number of designs was reduced by applying the constraints and then the trade-off defined through the requirements. This comes to only one concept which was the baseline of the satellite. At that stage this baseline was design for LEO 800 km and in the second period it was be extended to a large number of orbits. The concept used as the baseline is described below:

D.7.6 Mustang 0's final design

At the end of the second period, or phase B, a Critical Design Review took place to check the validity of the design. The main characteristics of the satellite can be seen below:

The orbit range of the satellite is from LEO (Low Earth Orbit) 700 km to MEO (Mid-Earth Orbit) around 10 000 km. GTO orbit is not currently available for several reasons from all the subsystems.

Shape	Octagonal
Mass	8.335 kg
Power available in light	26.4 W
Consumption	Depending on the mode of operation
Cost (platform)	£ 75,771
Cost (spacecraft)	£ 80,196

Table D.13: Main characteristics of Mustang 0 at conclusion of the project.

The lifetime of Mustang 0 can be estimated to one year but this is only estimations as some components would be manufactured on Cranfield Campus and then would be not space qualified for the first mission.

D.7.7 Further work

There are still some work to do on Mustang 0's design. The main areas to work on are the reduction of the power consumption due to the low margins, study of the risks on the satellite and the redundancy on Mustang 0. Besides, there is currently no protection on Mustang 0 against the debris and the radiations. Finally another possible thing to work on is to adapt the satellite to make it able to fly into a GTO orbit if it is possible.

D.7.8 Conclusions

At the end of the project, mass and cost requirements are validated and there are some margins for future developments of Mustang 0. Moreover, there is enough power onboard for all the missions and orbits but the margin is low but there are some solutions to increase this margin. The orbit range of the satellite is from LEO (Low Earth Orbit) 700 km to MEO (Mid Earth Orbit) around 10 000 km assuming that the radiation protections have been design. Finally, the lifetime of the satellite is estimated to one year but tests must be done to validate experimentally this value.

D.8 Mustang 0: Operations (Richard Gannon)

Space Research Centre, School of Engineering, Cranfield University

D.8.1 Introduction

Defining the modes of operations plays a critical part of the MUSTANG 0 GDP. Although the modes will remain more or less the same for different orbit altitudes and inclinations, when they occur and how often they occur will not. MUSTANG 0 must be able to demonstrate a degree of autonomy as contact with the ground station cannot be assumed throughout the period of one orbit. STK simulations help to give an understanding of how eclipse and sunlit durations vary with different orbits, thus determining when particular operations can occur.

D.8.2 Launchers

MUSTANG 0 is not launcher specific and should be versatile enough to be accommodated by a number of launchers considering that a launch will be obtained as a secondary or auxiliary payload.

Having obtained information on a number of launchers, it was clear that not all were suitable or able to take MUSTANG 0 as a secondary or auxiliary payload. The reasons for this were either because they were dedicated to military launches only or they simply didn't accommodate auxiliary payloads.

From those that did appear to be available, there were a few, such as Ariane 5 with ASAP and Delta IV with SAM that had dedicated auxiliary payload adapters and deployment rings. However, the majority simply indicated that secondary payloads could be accommodated depending on available space on particular missions. For the MUSTANG 0 mission the launcher interface is assumed to be that of the ASAP deployment ring as it appeared to indicate the worst case scenario. However, this will ultimately be launcher specific.

The opportunities that exist for insertion into a LEO are far greater than any other and this is one of the reasons why this region has had more focus than any other. However, it is quite possible for a launch to other orbit altitudes to be obtained and this has been taken into account.

D.8.3 Modes of Operations

The modes of operations of MUSTANG 0 can be characterised by the following flow diagram:

MUSTANG 0 should be able to demonstrate a certain degree of autonomy, with the ability to transmission between modes when not in contact with a ground station by means of time tagged commands. It should also be able to identify any problems on-board and have the ability to place itself in the relevant safe mode.

All things being well MUSTANG 0 will the majority of its lifetime operating between eclipse mode and normal mode (and sub-modes), defined by being in eclipse or in the field of view of the Sun. Operations whilst in eclipse will be minimal, with "useful" operations only occurring during normal mode. This is for power supply considerations. If MUSTANG 0 is not in one of the normal

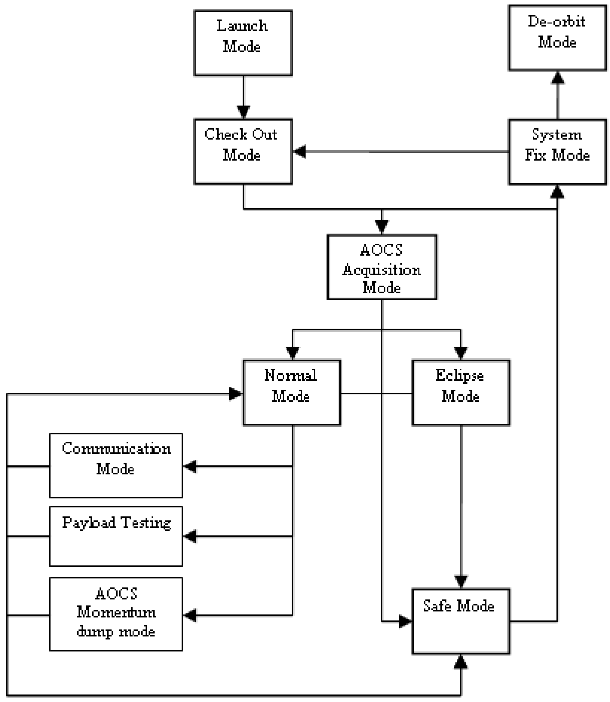


Figure D.11: Flow diagram illustrating the modes of operations

sub-modes, then it is using excess power; generated by its solar cells, to charge the secondary power supply (batteries) which are used as a power source whilst in eclipse. Only one mode can operate at any time.

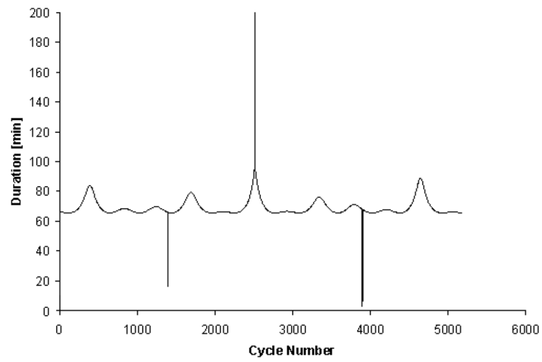
There exists allowable links between all modes and the safe mode (an input is shown by an arrow, an output by a line from the block). Many reasons for entering the safe mode are fixable; however, if this is not the case than MUSTANG 0 should be able to de-orbit, either autonomously or by a command sent by a ground station.

D.8.4 Mission Timeline

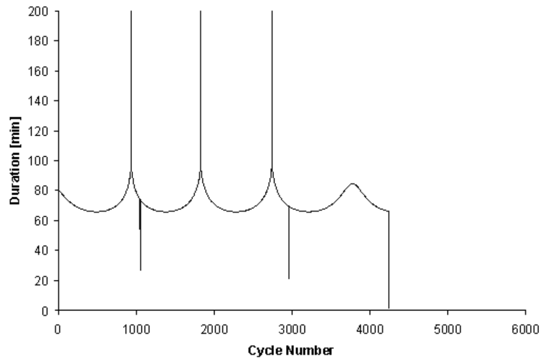
"Useful" modes of operations will only occur during times when MUSTANG 0 is in the field of view of the Sun. Because of this STK was used to run simulations over the period of a year (2005) to determine how sunlight and eclipse vary throughout the year, for different orbits and inclinations.

The orbits investigated were circular orbits of 450 km, 800 km and 10000 km with the addition of a GTO with a perigee of 200 km. The inclinations ranged from 0° to 90° in 5° increments for the circular orbits for the two LEO and the MEO and from 0° to 25° and 28.5° for the GTO. The special case of a sun-synchronous orbit was also run for the 450 km and 800 km orbits.

One particular phenomenon was highlighted from the simulations and that was the presence of lunar eclipses which occur twice during 2005 on 8^{th} April and 3^{rd} October and can effect up to three or four orbits, although this is dependent on the orbit altitude and inclination. Figure D.12 illustrates how the sunlight



(a) Inclination of 40°



(b) Inclination of 80°

Figure D.12: Sunlight duration for a circular 800 km orbit with inclinations of 40° and 80°.

periods vary throughout 2005 for two inclinations.

Lunar eclipses are shown be the downward spikes in the curves (the one to the far right exists due to the simulation ending at the very start of a sunlit period). The upward spikes refer to long periods in sunlight, up to 1 month in the 80° case.

Without a predefined orbit and inclination it was impossible to define a standard timeline. However the frequency that repeatable operations should occur has been highlighted in Table D.14.

The remainder of the time will be spent simply charging the batteries to survive eclipse periods. It is envisaged that this will need to occur for a vast percentage of the orbit period.

D.8.5 Conclusions

A substantial list of potential launchers has been produced for future MUSTANG projects, identifying current and future availability.

Operation		Frequency
System Monitor		Every 20 minutes
Reaction Wheel Dumping		Daily, at the very least
Communications		Dependent on orbit and inclination
Payload testing	Camera	Weekly
	Mobile Phone	Weekly
	Dosimeter	As often as possible
	De-orbit Device	Once

Table D.14: Repeatable operations and frequency of occurrence

The modes of operations have been clearly defined, indicating restrictions for when they can operate and the allowable transitions. MUSTANG 0 must be able to operate autonomously to a certain degree, changing modes by means of time tagged commands and also being able to identify problems and putting itself in a safe mode.

It was concluded that without a definite launch and hence orbit, it was unrealistic to define an exact mission timeline. However, operations that will occur many times throughout the mission have been identified and the frequency with which they should occur stated.

D.9 Mustang 0, On-Board Communication System (Kajal Haria)

D.9.1 Introduction

The design of communication subsystem for Mustang 0 nanosatellite starts with identifying the constraints imposed on it because the following design drivers:

- The mass, power and cost budgets of the system should lie within the limitations of the nanosatellite
- The system should be reliable for space communications
- The system should operate in the frequency band limits set by the ITU for space communications
- The system should provide efficient performance within the range of these constraints.

Apart from the above higher or top level limitations, the design is also constrained by the subsystems of the nanosatellite. These constraints are briefly discussed below:

- The AOCS for Mustang 0 demands for a communication system with omnidirectional coverage.
- The data rate of the system should be compatible with the payload and data handling unit. Also, it should be high enough so as not to exceed the data storage capability of the nanosatellite.
- The system should enable ease of interfacing and connection.
- The system should be compatible with the ground segment.

After identifying the constraints, the next step in the design is to calculate the link budgets. The link budget is the simulation of link or the communication channel in between the transmitter and the receiver and it calculates the minimum amount of power with which the signal should be transmitted from the transmitter in order to be accurately received by the receiver. The present work concentrates on the downlink budget analysis, i.e. when the signal is transmitted from the satellite to the ground station. The downlink budget calculations have been done for UHF, S and C frequency bands and for four different orbits:

- Circular LEO at 400 km altitude
- Circular LEO at 800 km altitude
- Circular MEO at 10000 km altitude
- GTO with perigee at 200 km altitude

Frequency Band	Mass (g)	Power (mW) (Transmit mode)
UHF	310	3630
S	1120	3400
C	1250	3400

Table D.15: Mass and Power Budgets of UHF, S and C Band Communication Systems

These calculations are then done for three different receiver antenna diameters of 12 m, 5.5 m, and 2.5 m assuming a parabolic dish antenna.

Based on the link budget calculations and constraints identified before, the components suitable for Mustang 0 nanosatellite in 3 frequency bands are selected and the Table D.15 gives their mass and power budgets.

It can be seen that the power budgets of all the three systems are more or less the same, however the mass budget of the UHF band system just about a third of the S and C band systems. Apart from having lower mass, the UHF band system components are smaller in dimensions and therefore can be easily fitted inside the nanosatellite. Also, in UHF band, two monopole antennas are used for omnidirectional coverage, which are 4 g in mass each and occupy negligible space on the outer surface of the satellite. Based on these factors, the UHF band communication system is selected for Mustang 0.

D.9.2 The UHF Band System Architecture

The Figure D.13 shows the detailed architecture design of the Mustang 0 communication system. All the components are space qualified and chosen from one manufacturer SpaceQuest, VA. A brief description of these components is as follows:

Modem

The modem MOD-96 is based on Gaussian Minimum Shift Keying and provides data rate of 9600 bps. The power consumption is 130 mW.

Transceiver

The transceiver TR-435 provides FM output at the bit rate of 9600 bps. It consumes 3.5 W of power and delivers 1 W RF output power.

Splitter

The splitter is a passive power divider circuit and does not consume any power. It divides the RF output power of the transceiver equally between the two monopole antennas i.e. each monopole antenna is fed with 500 mW of power.

Whip/Monopole Antenna

The whip antennas are made of flexible gold plated piano wire and have no power consumption as they are simple radiators. Their efficiency is about 99% and can deliver up to 50 W of RF output power. Each antenna provides a half doughnut shaped omnidirectional radiation pattern.

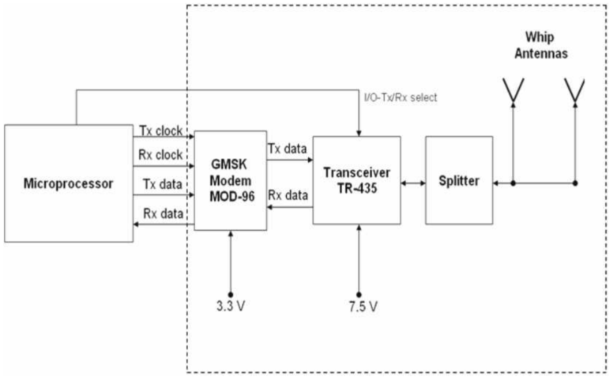


Figure D.13: Detailed Architecture of UHF Band Communication System

After considering the architecture of the system, the next step is to check its performance and suitability with the payload. As already stated, the communication system data rate is 9600 bps. At this rate, in a LEO, about 3 MB of data can be transmitted per day and in GTO about 2 MB can be downloaded per day, for the same amount of transmitter power, as shown in Figure D.14.

For the present configuration of payload for Mustang 0, this much downloadable data is acceptable, as the principal telemetry data are camera pictures which are 6.2 MB large. These can be sent back to earth in about 2-3 days.

However, the UHF band communication system will be rendered useless if for future missions, the payload demands higher bandwidth or data rate. In that case, other alternatives for higher bandwidths should be explored.

D.9.3 Alternative Design Concepts

The report briefly discusses some of these options for future missions:

A higher band communication system can be used for both uplink and downlink. Because of the requirement of omnidirectional coverage, the system may exceed mass and structure budgets. Moreover, the system may be bandwidth inefficient as a higher bandwidth is not required for uplink tele-command signals.

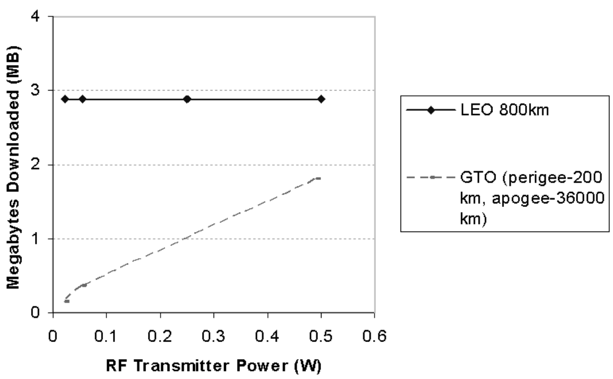


Figure D.14: Variation of number of Megabytes of data downloaded per day with RF Transmitter Power

A higher band transmission system can be used for downlink and a lower band reception system for uplink. The system becomes bandwidth efficient but also becomes more complex and therefore may not be desirable.

The system can be designed to provide limited coverage, so as to orient the satellite antenna towards the ground station whenever the satellite falls into communication window. Again, for such a design, a precise knowledge of orbit height, location of ground station, type of attitude control and placement of antenna on board the satellite is needed.

Hence, in order to design the system for higher data rates in future missions, a trade off analysis has to be done between the mass, power and structure budgets and the complexity of the satellite subsystems. This will also be influenced by the factors like degree of autonomy in the satellite, type of orbit, location and number of ground stations, and location and number of antennas on the satellite.

D.10 MUSTANG 0: Ground Station Data Handling (Paul Koronka)

Space Research Centre, School of Engineering, Cranfield University

D.10.1 Abstract

Communication protocols play an important role in the handling and distribution of data to systems either on a network or in direct connection with another system. This document addresses two topics with respect to the MUSTANG 0 software communications design: I) communications protocol identification and selection and II) programming of the application layer.

This document starts by identifying and acknowledging the more typical protocols that are used in Large Area Networks (LANs) and the Internet, specifically TCP/IP. TCP/IP has been well established within the networking community but possesses one key problem with it's assumption that all network errors e.g. packet loss, bit error problems etc are a function of network congestion. For a dedicated network link, such as MUSTANG 0, where there are not hundreds of systems communicating at the same time, this assumption fails the TCP/IP protocol in a satellite link. Alternatives are hence advised, mainly in the form of the CCSDS recommendation. This recommendation carries under it protocols that have are adaptations to TCP/IP but for space dedicated links. Another strategy is to build a protocol suite specifically for MUSTANG 0.

A demonstrative application layer has been written in C. This program uses standard TCP/IP that simulates the data exchange between a server (MUSTANG 0) and it's client (the ground station). The concept of splitting the raw image file (<6MB) into smaller segments is used and tests have shown the program to run effectively.

D.10.2 Introduction

The first section of the report concentrates on recommending the appropriate protocols that should be used with MUSTANG 0. Protocols are sets of instructions on how to pass data between multiple systems using a communications hardware link. Later chapters allow the reader to become aware of the structure of most protocols used. Although not covered in detail, these sections will provide a starting point for future projects to pick up on. Chapter 4 of [11] then concentrates upon the most common protocol used in today's larger networks and the Internet – TCP/IP. This section is used to study a protocol in more depth and lists the various attributes of the protocol in modern day networking structures, and also lists the negatives of using this implementation over a satellite link. At the end of Chapter 4, an alternative set of protocols as advised by the CCSDS recommendation are introduced and addresses these negatives identified over a satellite link.

Further into the document, specifically Chapter's 6 through 8 of [11], identify the main source of work – programming the application layer. The application layer defines the user interface between the lower network layers and the user. This ultimately controls what data is to be sent. These sections identify MUSTANG 0's data needs and demonstrate example programs that simulate these data needs in software terms. Full documentation of the code is included within these chapters.

Protocols not only play a large roll in the sending and receiving of data, but also in the safe arrival and integrity checks that are needed to ensure negligible bit errors.

D.10.3 MUSTANG 0 Requirements

MUSTANG 0 has two categories under which the communication process can be split:

1. Ground station communication.
2. Satellite communication & data handling.

Ground station communication

The ground station has the following responsibilities:

1. Sending command data and uploading software "patches".
2. Receiving data/image files.
3. Managing this data to respond appropriately.

Satellite (MUSTANG 0) communication

MUSTANG 0 must control the following:

1. Receiving command data, interpreting and preparing data.
2. Sending this prepared data if required.
3. Storing/replacing data received.
4. Store system check, payload and image files ready for download.
5. Half duplex link i.e. can't send/receive at the same time.

D.10.4 Software requirements

Converting the above system requirements in to software requirements produces the following steps:

1. Define network/communication protocols to be used.
2. Define data that needs to be sent and received by both ground station and satellite.
3. Produce command tree that is provided by MUSTANG 0 to the ground station.
4. Manage the link in such a way that the half duplex problem is solved.
5. Create user interface (application layer).

It is these software requirements that will be specifically addressed in this document.

D.10.5 Summary of TCP/IP and the CCSDS recommendations

The TCP/IP suite is really the cornerstone of modern protocol systems and their understanding is critical for any extensions to these protocols.

The tried and tested TCP/IP works very efficiently over standard point to point and connected networks that need a wiring infrastructure. i.e. when the only problems that can occur are with network congestion.

Since MUSTANG 0 will be communicating over a direct link, the use of IP almost becomes irrelevant since the "hopping" process will become redundant. If the communication infrastructure was to include a network of satellites then this hopping process would need more thought, hence the reason why the Internet Protocol has been pushed to one side.

There are various extensions to the standard TCP that have been adapted for space (wireless) use, but of particular note are the CCSDS communications recommendations. Numerous documents are available that list the key concepts behind transport & network layer protocols for wireless applications, specifically SCPS-TP and SPCS-NP.

Currently, there will be no in depth use of the CCSDS recommendations since implementing these extensions would require the programmer to access the data link layer and program the higher layer protocols individually. This task really is the concern for researchers and not a 5 month study.

Since there may be a problem with the half-duplex transceiver link and the packet acknowledgement issue, it may be the case to look into a new more specific protocol – perhaps for use with a Cranfield built grand station. This may or may not be needed depending on whether packet acknowledgements can simply be "switched off" within the SCPS-TP protocol.

As it stands, the SPCS protocol suite seems to provide the best options for MUSTANG 0.

D.10.6 The Application Layer

Segmentation of the raw image file is necessary to apply more control over the link. Since the greater chance of a bit error occurring is through transmission of larger files, it is better to segment this file. This can also provide more control over the lower-layer protocols.

The header information governs what data is being sent and received and is important to the ground station user in terms of identifying problems with the link.

D.10.7 Conclusion

Although SCPS provides a good set of protocols to overcome the shortfalls of TCP/IP over a wireless link, there are set backs. It is still unclear whether the protocol can have the acknowledgements field switched off. This is important in the case of a half-duplex link with MUSTANG 0 as it may prove difficult for the transceiver to switch between transmitting and receiving modes quickly. This may not be possible, or may even consumer more power. This potential delay may cause sufficient congestion to the extent that MUSTANG 0 becomes a "bottleneck" in the communications structure. This is very undesirable.

However, the protocol is set as a guideline and hence is not strictly standardised. It is the author's decision to recommend this protocol be adhered to as compatibility to future space systems may prove useful. If this recommendation is used as the standard over wireless links (such as TCP/IP is the standard for the Internet) then compatibility for future missions is desirable.

Because of this fact, it would seem possible to implement a new version of the SCPS-TP protocol that simply neglects acknowledgements of the packets. It would be possible to take control of packet acknowledgement away from the transport layer and use the application layer to control what should be acknowledged and when.

The application layer program written and tested demonstrated the key principles behind the MUSTANG 0 project in terms of communicating onboard data to the ground station. The primary objective was to show the use of a "image" cutting function that could segment the large image file into much smaller images for transportation, as this was the most difficult challenge. In all the tests show that this was a success.

D.10.8 References

Data communications, computer networks and open systems, 4^{th} edition. Fred Halsall. Wokingham : Addison-Wesley, 1996.

Internetworking with TCP/IP: principles, protocols and architecture, 3^{rd} edition. Comer, Douglas E.; Englewood Cliffs : Prentice-Hall,1995

TCP Extensions for Space Communications, Robert C. Durst et al. (see Appendix F)

`http://www.elliottsweb.co.uk/T171/TMA04/#Intro`
`http://www.pcsupportadvisor.com/nasample/c04100-2.pdf`
`http://www.ietf.org/rfc/rfc813.txt`
`http://www.rhyshaden.com/tcp.htm`
`http://public.ccsds.org/default.asp`

D.11 (Kristina Larfars)

D.11.1 Abstract

The MUSTANG 0 is a group design project carried out by students from the MSc Astronautics and Space engineering program at the School of engineering at Cranfield University. The baseline of the project was to research the possibility of a nanosatellite concept that would work as a test bench for Microsystems technology (MST) applications for space. The top level constrains were to have a low mass low cost satellite that should be able to piggy-back on a wide range of launch vehicles. The project was divided into Work packages where every team member of the group had their own field of research. My contribution was in the electrical power subsystem, were my work has been to identifying potential hazards and to produce a power timeline. The timeline included setting up a power budget of the power consumed by the other subsystems and doing the solar cell configuration.

D.11.2 Potential Hazards

So by starting looking at the potential hazards regardless of which orbit and for what lifetime the satellite will have. Some of the potential hazards are listed below:

- Battery explosion (due to thermal, excessive power drain, etc.)
- EMC rating (What is acceptable?)
- Spacecraft Charging (Electrical sparks)
- Radiation (Can we survive radiation?)
- Debris impact (Shielding? Solar panels?)
- Polarized particle impacts (Are we orbiting the polar circles? Impact?)

The hazards above will have different levels of impact on the circuit. A **battery explosion** and big **debris impacts** will of course destroy the entire circuit and the satellite will die since no subsystem will have a power supply. The biggest reason way the battery would explode is if we over charge it. Therefore a monitoring circuit for the batteries is necessary to minimise the risk for this event.

Other hazards will have smaller direct effects but in the long term even this could have a big impact on the satellite health such as solar panel degradation. One other aspect is the **Spacecraft Charging** that can arise from the fact that the plasma in space gives different parts of the spacecraft surface different voltages potentials. If these potentials reach a certain threshold value sparks between surfaces can occur and damage electronic equipment. For this a simulation, in Spenvis, will be carried out to see if any cautions are needed. Spacecraft charging is a more common event on bigger satellites or at satellites with probes, but it can occur on small satellites as well.

On other hazard are the **Radiation levels** of protons and electrons, and the **Debris impacts**. Radiation mainly gives degradation to the circuitry and

Modes / Subsystem	Voltage level (V)	Check Mode (W)	Normal Mode (W)					Eclipse Mode (W)	Safe Mode (W)
			Normal	AOCS unload	Communication		Payload		
					Transmitting	Receiving			
De-orbit device	5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	
Payloads	5						0.35		
AOCS normal	7.5	4.8	4.8		4.8	4.8	**4.8**	4.8	
AOCS unload	7.5			5,94					
CPU	3.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3
Communication T	5 to 7				3.8				
Communication R	5 to 7	1.0	0.1	0.1		1.0	0.1		1.0
Power unit	5	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Total		**16.4**	**15.5**	**16.6**	**19.2**	**16.4**	**15.9**	**15.4**	**11.1**

Table D.16: Power consumption in the different modes of operation

especially the solar panels. Digital equipment is especially sensitive to smaller debris impacts since they are very sensitive to single event upsets. An impact may change a level from a '0' to a'1' or the other way around. This could cause that the wrong command can be sent to a unit. To try to delay the degradation different kind of shielding will be necessary. The degradation of the solar panels needed to be considered in the power estimations so that the power supply is over dimensioned at the beginning of lifetime.

One other thing to concern is the **EMC rating** (Electro Magnetic Compatibility). Electronic equipment generates Electro magnetic disturbance and some components or sensors can be sensitive to these levels of EMC. Do we have sensitive equipment onboard? How would a stable Ground plane be located in the satellite?

D.11.3 Timeline

Power consumption

To be able to do a power timeline for one orbit or for a satellite lifetime you need to have a good understanding of the power consumed by the subsystems in the different modes of operation. Since some of the subsystems will not be switched on during all modes of operation. How the subsystems are connected to the different modes and the power consumed by them can be seen in Table D.16.

D.11.4 Solar panels

To generate power onboard the satellite solar panels are used. We specifically looked at two different germanium cells from Spectrolab with the same cell structure but with different efficiencies (Soeberg, Philip (2004/2005)). With these solar cells calculations were made with fitting different cell sizes on to the satellite structure to see from which one the most power could be drawn. The different cell sizes were mounted directly on the octagonal shaped structure.

For the three different sizes of cells the 2x4 cm cell in a constellation of 3 cells per panel gave the highest power level as seen in Table D.17.

The above values are when the solar panels are illuminated at a 90° angle from the sun, and before the degradation.

Cell size	Efficiency (W)	Series of 3 cells /string (W) Top	Payload	Side	Series of 4 cells / string (W) Top	Payload	Side
2x4 cm	21.5	24.4	9.1	23.4	24.1	7.0	22.7
3x4 cm	21.5	23.6	8.4	22.6	23.7	8.4	23.4
7x4 cm	21.5	21.9	7.3	23.4	22.7	6.5	23.4
2x4 cm	28	31.6	11.7	30.4	31.3	10.8	28.9
3x4 cm	28	29.8	10.8	29.3	30.7	10.8	30.4
7x4 cm	28	28.5	9.5	30.4	29.5	8.4	30.4

Table D.17: Power table for all cell sizes and string configurations.

The only off the shelf cell available from Spectrolab are the 7x4 cm cells. This, as well as the other cells, cost $300 per cell. But to have the 2x4 cm or 3x4 cm cells there will be an additional cost of $M 1.2 [14]. For this project there can be no justification in the increased power levels achieved by using smaller cells by the extra cost. The configuration of 7x4 cm cells gives a total amount of 132 cells, which gives a total area of 3696 cm^2. This gives an estimated weight of 0.76 kg, where each cell has a weight of 5.7 g. And a total cost of $39 600.

The final layout can be seen in Figure D.15.

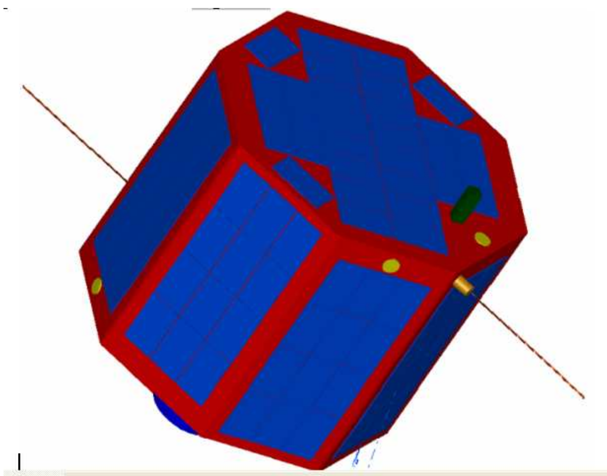


Figure D.15: Final layout of the solar cells

D.11.5 The Power timeline

The power timeline was made for the periods in the satellite lifetime that would have the largest impact on the power system. Which of course are the orbits with long eclipses. This was divided into two different cases to make it easier to overview the work.

1. Normal maximum eclipses
2. Worst case eclipses doe to lunar eclipses.

	Safe mode 11.1 W	Total	Safe mode 8.1 W	Total
LEO 800 km	4	10	1	8
MEO	5	12	2	8
GTO	14	20	9	18

Table D.18: Extra batteries need for the different orbits

The result from the calculations was that the satellite would survive the normal maximum eclipses with the present battery configuration of 6 cells. (Soeberg, Philip (2004/2005)). But for the worst-case eclipses al orbits needs extra batteries to be provide the satellite with enough power. The amount of cells needed can be seen in Table D.18.

While doing the power timeline for the 800 km LEO orbit I realised that even the normal maximum eclipses were hard to survive without starting to make changes in the modes of operation. Therefore I made an approximate calculation to se, which the lowest orbit was suitable, in terms of power. To do so I looked at how many percent of the range of one years of orbits we could do something else then charging the batteries when we was in the view of the sun. As estimation I used a minimum value of 5 min over the charging time as a minimum for it to count as a usable orbit. This gave the lowest orbit to be 600 km.

D.11.6 Conclusion

For the potential hazards the monitoring circuit was built by Philip Soeberg to minimise the risk of a battery explosion. If the satellite goes through the van Allen belts or in a high altitude orbit there is a risk off arcing caused by Spacecraft charging. Putting a spike on the structure to emit the electrons may prevent this.

For the configuration of solar cells the work carried out chose that of the choice of using 21.5% or 28% efficiency cells the most efficient one is necessary to be able to generate enough power to system. In terms of cell size because of the low cost restriction the 7x4 cm cells was the only one that could be used even if smaller ones had been better in terms of power output. The cells would preferably be strung in the 4 cells per panel configuration to keep the voltage level from the panels higher then the one required from the subsystems.

To survive the longer eclipses (lunar + earth) extra batteries are necessary. The number of extra cells depends on the orbit, but to be able to go to all stated orbits, 14 extra batteries are required.

The range of orbits for the power system is limited by the fraction of eclipse and sun times. The calculations of the LEO orbits gave a minimum altitude of 600 km. These because of the low fraction of orbits where possible payload and communication mode could be entered.

D.11.7 References

Soeberg, Philip (2004/2005). *MUSTANG 0: Electrical Power subsystem, Architecture and design.* MSc in Astronautic and Space engineering, Group design projects. School of engineering, Cranfield University 2005.

D.12 Executive Summary: Mustang0, Ground Communication System, (Benjamin Marchand)

D.12.1 Abstract

A nanosatellite is designed to perform specific functions in space and it is the responsibility of the operation center to ensure that the objectives of each part of the mission are attained. For that, the ground segment infrastructure has to be suitable and ready to support the mission for the described requirements and constraints.

The objective of this study is to define the type and number of ground facilities that will be the most suitable to support the MUSTANG0 nanosatellite project, dealing with cost and time constraints as well as with the mission requirements.

The different functions that performs a satellite ground control facility are described to introduce the ground system and to choose the type of ground station required. Then the payload data processing and data handling determine the number of ground stations to be used. Finally, a list of ground terminals available is given dealing with the unknown orbit inclination that will be determined by the launch opportunities. The access times have been simulated using STK to evaluate the amount of data that we can expect and to perform the power management which is a critical issue for a nanosatellite mission.

The fact that this project has to be a low-cost one leads to the use of a single small ground terminal as the best solution for the mission. A first overview of the design and conception of such a low-cost ground station is given at the end of the individual report.

D.12.2 Introduction

Ground stations acquire mission data from the spacecraft and its instruments and transfer it to the data users. Ground systems consist of ground stations and control centers working together to support the spacecraft and the data user. A satellite ground control facility performs general functions during the mission life of a satellite like:

- Orbit determination and maintenance
- Attitude control
- Commanding and telemetry processing
- Performance determination and evaluation
- Planning and scheduling

Depending on mission requirements such as payload operations, performing any or all of these functions can be quite complex.

D.12.3 Ground Satellite Link Analysis

The first step in the project was to think about the type, number and location of ground stations that could be available, dealing with cost and time constraints as well as with the mission requirements. Concerning the type of ground station, we can either use existing ground stations or build and use a new small ground station. The small ground station is the solution that offers most advantages and because there are very few ground stations available using UHF band, a first study has been made on the conception of a low-cost ground station here in Cranfield University.

Concerning the number of ground stations, it depends mainly on data handling, and for that again two solutions are possible: We can either use multiple ground stations or store data onboard & forward them to a single station. For a cost point of view and whatever the orbit is, the second solution appeared as the best solution for the project. Moreover, by considering the type of payload onboard the spacecraft, it is not necessary to send data to the ground in real time.

Then the next step for the ground communication system was to realize the Ground Satellite Uplink Analysis. As well as for downlink analysis, this mathematical model for uplink has been performed for three different frequency bands. For each frequency, the analysis has been done for four orbits and three different ground antenna's sizes. But the uplink budget is less restrictive than the downlink budget because we are not limited on transmitted power

D.12.4 Ground Stations

For the location of the ground center, two possibilities have been considered:

1. Ground stations in UK which represent the easiest way to receive information from the spacecraft and send back the data to Cranfield. They are relatively small ground terminals that could contribute to a cost reduction for the mission and they offer different capabilities like S-band or VHF and UHF bands.

2. The second possibility is the ESA Network with Ground stations all over the world (like Kourou, Villafranca, Kiruna or Redu). The stations in this network could potentially provide support to our mission, under the assumption that TT&C (telemetry, tracking and commanding) will be in S-band.

Along with the ground stations capabilities, there are other important characteristics to know for a given ground station like the planning of the station, its timescales and also the cost that implies its use for the routine phase as well as for the preparation of the station.

D.12.5 Access Times Simulations

After the choice of the different ground stations available, in order to have a complete database, the access time which is the time of communication between the spacecraft and the ground has been calculated to be able to decide, once the orbit will be defined, which ground station is the most suitable for the project.

(a) UK ground station (b) ESA ground station

Figure D.16: Typical ground stations

The orbital access will mainly be a function of the latitude of the receiving ground station. Hence, to have a good range of latitudes, six potential ground stations have been examined.

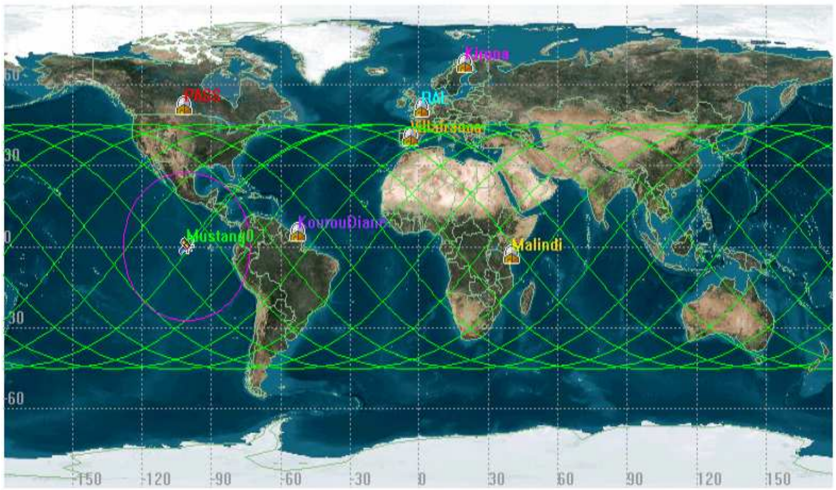


Figure D.17: Communication coverage illustration calculated using STK.

The software Satellite Tool Kit (STK) was used to perform the calculations of access times between the satellite and the different ground stations for each orbit and each inclination considering that the satellite can not communicate with the ground when it is not in direct view of the Sun and when it is at an elevation angle below 10°. The results have been recorded by month over a period of one year and all these access times have been plotted in order to easily determine the most suitable ground stations.

Small Terminal

The use of our own ground station for the operation of the nanosatellite is one of the best solutions. In this first study of a low-cost experimental ground terminal, it is essential to define the objectives that justify the design and building of the station:

1. The first one is the reduction of the overall cost of the mission
2. Then this terminal will also have to fit to the mission requirements
3. The third objective is an educational one. Indeed, students could be able to test and verify their knowledge through the operations of this small ground station.

The configuration of such a small station is quite simple. The point to notice is that with only one or two computers running under the windows operating system and commercial of the shelf components and software, we can build and use a low-cost ground station, which could be very useful for the university.

D.12.6 Conclusions

Considering data handling and the fact that there are very few ground stations available using UHF band, a low-cost small station is the solution that offers most advantages. Obviously, as the Group Design Project ran from October 2004 to March 2005 there was not enough time for the development of a Cranfield ground station. However, that does not mean that we could never use such a station. An overview of the objectives and requirements for the building of a low-cost terminal has been done but for further work in the project, it could be interesting to have someone working on the design and development of such a ground installation. And if the design can not be performed for the MUSTANG0 project, it could be interesting to use a station already developed by another university in order to see the real difficulties that implies the conception.

D.12.7 References

Elbert, B. (2001). *Ground Segment and Earth Station Handbook.* Artech House, Boston.

ESA. Ground stations. `http://www.esa.int/SPECIALS/ESOC/SEMZEEW4QWD_0.html` (accessed 20th March 2005)

Hsiao, F., Liu, H. and Chen, C. (2000). *The Development of a Low-Cost Amateur Microsatellite Ground Station for Space Engineering Education.* Global Journal of Engineering. Education, 4(1), 83-88.

D.13 Electrical Power Subsystem, Architecture and Design (Philip Soeberg)

D.13.1 Abstract

The objective of this paper is to describe the development of the architecture and design of the electrical power subsystem (EPS) for the Mustang0 nanosatellite. Mustang is a University led space project that aims to demonstrate the potential of Microsystems technology (MST) for space. The research programme is carried out by Cranfield University, with EADS Astrium as its primary industrial partner.

This report analyses the architecture and design of an electrical power subsystem for the Mustang0 satellite, and describes the development steps performed to reach the final configuration. The primary source of power during sunlight is provided by the body mounted ultra triple dual junction GaInP2/GaAs/Ge solar cells. The body mounted solar cells produce an average power of about 26 W, which is sufficient energy to power all the subsystems. While in eclipse, the power is provided by a battery pack of Lithium-Ion cells, providing up to 36 Whr of power. The battery pack can be extended with additional batteries depending on the requirements of the final orbit.

The design of a complete power supply has proven a greater task than first assumed. The difference between space applications and terrestrial applications are enormous, so compromises had to be done from the very beginning of the project. The final result is a complete power supply, though not space graded. It serves as a first version power supply from where next level development can be spawned. A breadboard model of either the whole or parts of the system can provide a good basis for tweaking the design, eventually leading to the space ready power supply.

D.13.2 Summary of chapters contained in the report

Chapter 1 – Introduction to the electrical team

The electrical team for the academic year 2004/2005 consists of two students, Kristina Lärfars and Philip Soeberg. Our responsibility is the entire electrical power subsystem (EPS) on the satellite. This ranges from identifying all the requirements, studying the environment of where we must operate, generating power in one form or another, processing it and distributing it, all while maintaining an extremely high level of fault and safety tolerance.

My part, the EPS Architecture and Design, fundamentally deals with the architecture and design of a power supply unit for our satellite.

The power supply unit (PSU) covers the satellites source of power, ranging from solar panels and batteries to charging and regulation. Its main responsibility is to provide the satellite subsystems with a reliable source of power during the entire mission. As the PSU is a single-point-of-failure unit, special care must be taken to ensure its reliability. Should the PSU fail, the mission will effectively be lost.

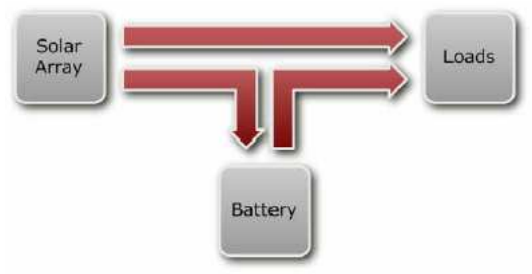


Figure D.18: Key components of the power supply unit.

Chapter 2 – Technology Study

The technology study investigates the background of Solar cells, batteries and radiation effects on electrical components.

Solar cells, as a producer of power, are quite tricky as they should be considered a varying voltage, varying current source. The voltage and current are nonlinear dependent on each other, which adds to the complexness of extracting power from it.

By utilizing a technique known as Maximum Power Point Tracking it is possible to gain an additional 10% more power than by simply connecting the cells to the standard input. As the current depends on the amount of irradiation absorbed by the different layers, and the voltage depends on the temperature of the cell, it is virtually impossible to develop a mathematical model describing this maximum power point. Instead a microprocessor is used to constantly monitor the voltage and current drawn from the cells. The microprocessor, connected to a DC/DC step-up converter will instruct this converter to increase the output voltage on step at a time, until the voltage on the input side starts to drop. At this point, the microprocessor instructs the converter to decrease the output voltage to regain the voltage level on the input side.

Different battery chemistries are studied in detail as to identify the optimal type for our project. Charging and discharging pros and cons are considered, and a conclusion on why Lithium-Ion batteries are best is discussed.

The effect of high energy protons, which are virtually impossible to shield against, is investigated. A single event effect is a nasty problem onboard a satellite. Two problems can occur when a high energy proton penetrates a transistor.

1. A Single Event Upset causes the status of the transistor to switch. Where it was a zero before, it is now a one. This results in data loss or data corruption.
2. A Single Event Latch Up causes an MOSFET to start conducting current which is especially dangerous in the power supply as excessive surges can occur due to the high power circuitry present. Protection circuitry must be developed to prevent this.

Chapter 3 – Identifying the correct source of power

The basic requirements and drivers for the choice of solar cells and batteries are discussed. We finally chose Spectrolab's Ultra Triple Junction solar cell.

The Panasonics CGR18650C Lithium-Ion cell was chosen as this particular cell has undergone extensive testing for future space based missions.

Chapter 4 – The power supply

The main objectives of the power system are:

- Maximize the power available to the payload.
- Maximize resilience to SELs (Single Event Latchups).
- Isolate failures from causing other systems to fail.
- Operate with a high energy and space efficiency.

With these simple requirements defined, I began investigating how to build a power supply. I sadly realised that to obtain specific information on space graded components proved extremely difficult, as direct contact with the manufactures military department often was required.

Instead I chose to continue the development of a power supply, this time with commercially off the shelf components (COTS). It is important to stress that no single component in the current design is space graded, but the design should still provide the bases for further development.

D.13.3 Conclusions

Throughout this project I have been involved in the design of an entire power system for a satellite. Where I started off thinking "How difficult can this be?", I now realise that such an endeavour is not a trivial task.

Building terrestrial applications is a fairly straightforward, simply because factors such as pressure, unlimited power supplies (i.e. the wall socket), and good thermal properties exists. On a satellite on the other hand, there is nothing that will help you make it easier. Every single watt has to be accounted for, as heat dissipation literally can destroy the electric circuitry if not being dealt with. Vacuum is another challenging factor, as most batteries and capacitors are built under less than 1 atmosphere pressure.

Nevertheless, it has been a great adventure and I hope the next project team can benefit from some of my experiences.